UNIVERSITY OF ILLINOIS BULLETIN

ISSUED WEEKLY

Vol. XXIV November 16, 1926 No. 11

[Entered as second-class matter December 11, 1912, at the post office at Urbana, Illinois, under the Act of August 24, 1912. Acceptance for mailing at the special rate of postage provided for in section 1103, Act of October 3, 1917, authorized July 31, 1918.]

AN INVESTIGATION OF TWIST DRILLS

PART II

BY

BRUCE W. BENEDICT

AND

ALBERT E. HERSHEY

BULLETIN NO. 159

ENGINEERING EXPERIMENT STATION

PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

PRICE: FORTY CENTS

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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PART II

BY

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AN INVESTIGATION OF TWIST DRILLS
PART II

I. Introduction

1. *Introductory Statement.*—This investigation of twist drills is the second of a series which has been planned to determine the factors relating to the design and performance of this widely used production tool. Results of the initial investigation were published in Bulletin No. 103 of the Engineering Experiment Station in 1917. As stated in the preface of that bulletin, the first part of the investigation was essentially preliminary in scope with the object of determining the general characteristics of the twist drill as a cutting tool, and of opening the way for further and more extensive investigations in the phenomena of drilling. The second part, with which the present bulletin is concerned, deals specifically with the relation between helix angle, and torque, thrust, and endurance of the drill when drilling in gray cast iron and steel.

During the late European war the original program of tests was temporarily abandoned, but in 1920 it was revived, and with it plans for an improved testing equipment. A heavy duty drilling machine was installed and equipped with a dynamometer capable of measuring forces and recording data beyond the capacity of the original apparatus. As the present dynamometer is of novel design it is described in some detail in the following pages. A period of two years has been employed by the authors in obtaining the results herewith presented.

Since the publication of Bulletin No. 103 investigators in both the United States and Europe have added to the store of knowledge on the subject of drills and drilling, but as yet no work has been done in this field comparable with Taylor's classic experiments on lathe cutting tools. As a factor in the production of metal goods the process of drilling ranks in importance with turning or milling, and is, therefore, worthy of a thorough and systematic study with the aid of precision apparatus. An investigation of the magnitude which such a study demands can be accomplished within a reasonable period of time only through coöperative effort on the part of drill and drilling machine manufacturers, and laboratories equipped for scientific testing. Such an investigation would accomplish in a reasonable time what would require years of effort by individual investigators working independently, and would furnish information in the immediate future which should remove the twist drill from the realm of the rule-of-thumb.

2. *Object of Investigation.*—In the initial investigation of twist drills reported in Bulletin No. 103 the fact was disclosed, and, so far as the authors are aware, for the first time, that power consumption at the drill point is influenced more by changes in helix angle than by any other one factor of design. It was found that at heavy drilling rates the power required at the drill point in gray cast iron was reduced more than 20 per cent by increasing the helix angle from 26 degrees to 35 degrees. As these tests were conducted on gray cast iron only, the results were not considered generally applicable until similar tests had been made on the carbon and alloy steels commonly used in industry. The question of drill endurance, especially in drilling steel, was likewise an undetermined matter. It was, therefore, decided to make a comprehensive study of the relation of the helix angle of twist drills to the power consumption and endurance, in both gray cast iron and steel, with the object of determining what helix angle best satisfies the inseparable requirements of (a) economy in the use of power and (b) resistance of the cutting edge to wear and destruction.

3. *Acknowledgments.*—The testing apparatus was constructed by the mechanical staff of the Machine Laboratory; the test blocks of gray cast iron were made in the Foundry Laboratory; the metallographic work and heat treating of steel test blocks was done in the Forge Laboratory. The Central Steel Company, Massilon, Ohio, donated all of the alloy steels used in the test. The Fulton Company, Nashville, Tennessee, coöperated by furnishing "Sylphons" for the dynamometers. Drills of special dimensions were supplied by the Detroit Twist Drill Company and by the Cleveland Twist Drill Company. The New Departure Manufacturing Company donated one large ball bearing for the drill dynamometer. Mr. Klass Knibbe, Holland-American Foundation student, Delft, Holland, assisted in the conduct of the tests for a period of three months.

II. Description of Apparatus

4. *Drilling Machine.*—The drilling machine used in this series of tests was made by the Minster Machine Company. It is of the heavy duty type, with 12 speeds and 12 feeds arranged particularly for testing purposes. The speed range is from 35 to 650 r.p.m., in geometric progression with a ratio of approximately 1.30. The feed range is from 0.0084 to 0.1000 in. per rev., likewise in geometric progression with a ratio of approximately 1.25.

Slippage between the driving motor and the machine is avoided by employing a 5-in. Link Belt drive between the two. In the machine itself, the power for driving and feeding the drill is transmitted entirely by means of gears. Ball bearings are provided throughout the transmission gear box and these, together with provision for ample lubrication of all gears and bearings, insure a minimum power loss. Another noteworthy feature is the main spindle drive. A large cylindrical sleeve is driven directly by gears, and this sleeve in turn drives the main spindle through the medium of two wide and deep keyseats extending the full length of the sleeve and engaging two hardened driving keys mounted in the driving head. The driving head is thus supported and guided in the driving sleeve while free to move up and down without binding even when the machine is operating under a heavy load.

5. *Motor Drive.*—The power for driving the drilling machine is supplied by a two-phase 25-h.p. induction motor operating at 1200 r.p.m. The method of mounting this motor so that it may serve as a dynamometer for measuring the power input to the drilling machine is shown in Figs. 1, 2, and 3. As will be seen from Fig. 3, the frame of the motor is bolted to two brackets R which are in turn mounted on ball bearings at S and T so that the whole is free to oscillate. One of these trunnion bearings is hollow, permitting the motor drive shaft to pass through it. This extension of the drive shaft carries the driving gear and is supported at the end by the outboard bearing U. An arm V screwed into the field casting has at its outer end a hardened steel button which bears against a similar button mounted in the end plate of the sylphon X. By this arrangement the torque reaction of the motor frame is transferred to the hydraulic system of the dynamometer. The pressure in the dynamometer system, which is proportional to the motor torque, is indicated by two diaphram gages and recorded by a Bristol recording gage.

The motor-torque dynamometer is calibrated in place by hanging standard weights from an arm projecting from the motor casting on the side opposite to that on which the dynamometer is located. The length of this arm being the same as that of the arm which applies the load to the dynamometer sylphon, the pressure in the system corresponding to a given dead weight will be the same as that which exists when an equal force is applied to the sylphon due to torque reaction. The gages may, therefore, be calibrated to indicate the motor torque in ft. lb. The torque and the motor speed being known, the latter indicated by a tachometer (M in Fig. 4) driven directly from the shaft of the motor,

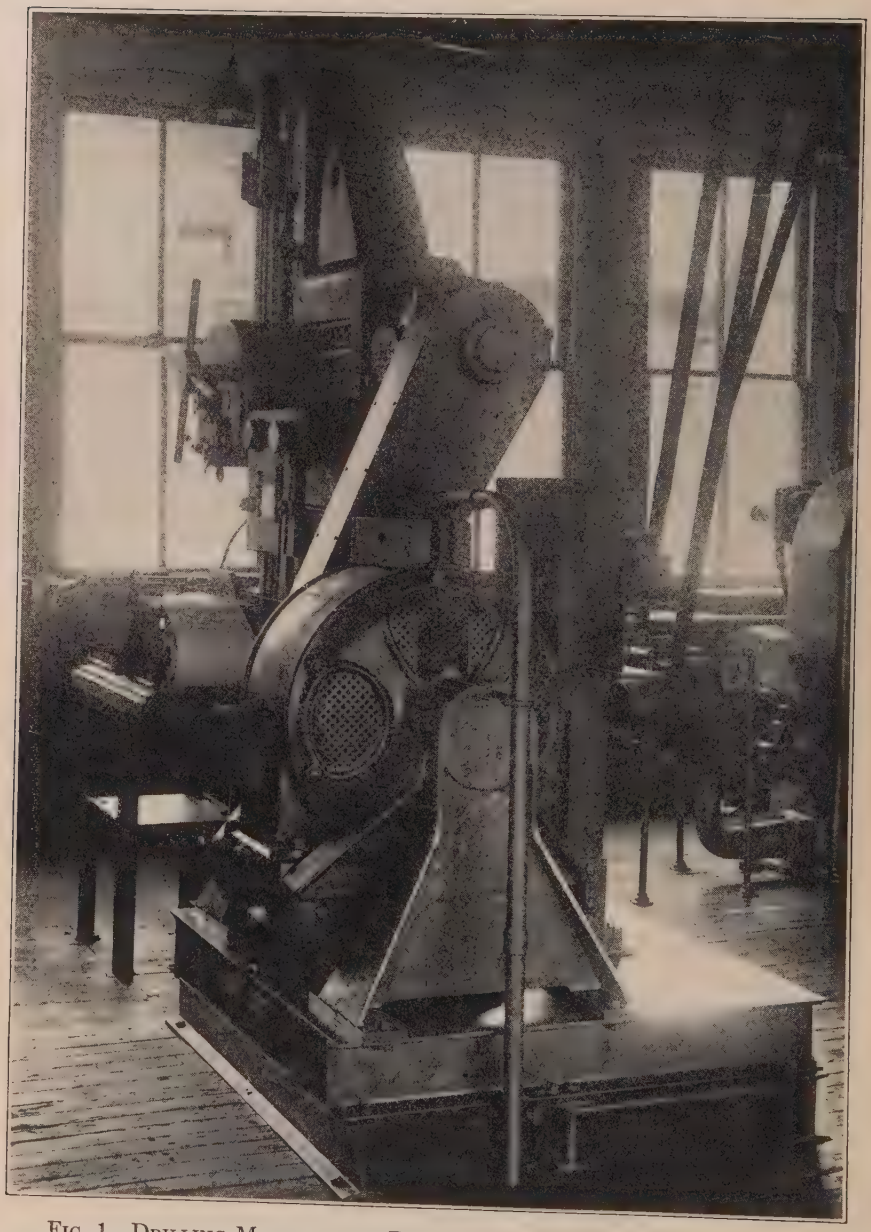


FIG. 1. DRILLING MACHINE AND DYNAMOMETERS, VIEW FROM THE REAR

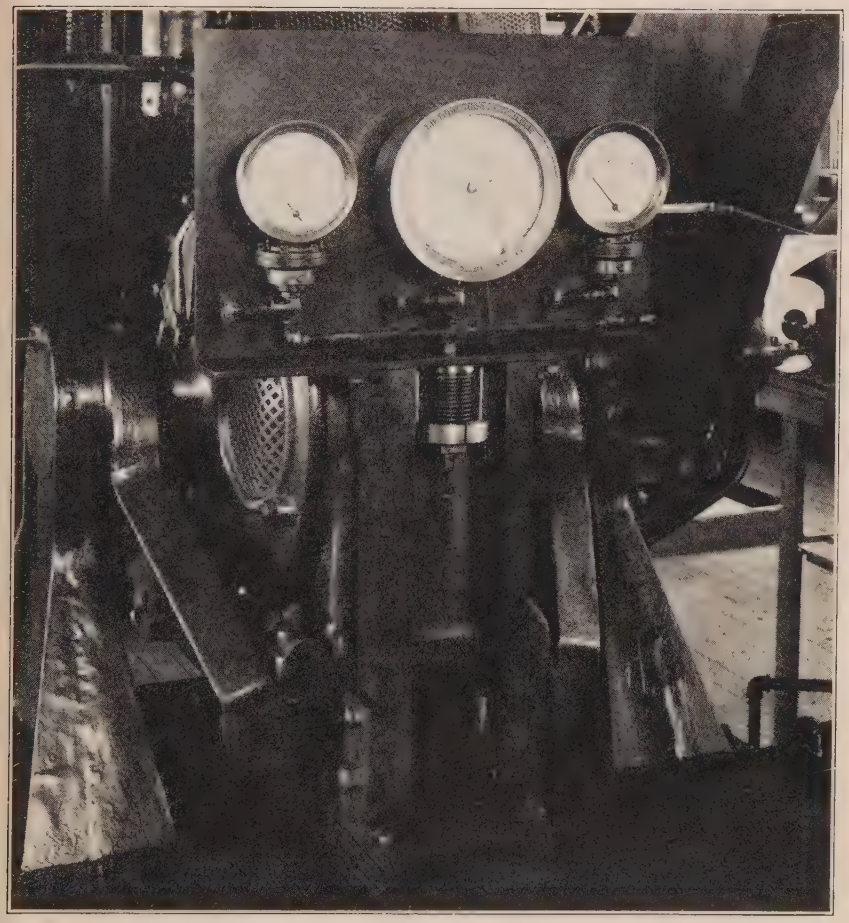


FIG. 2. DRIVING MOTOR AND DYNAMOMETER

the power required to drive the drilling machine, independent of the motor losses, may readily be calculated.

The sylphon, which forms the load absorbing unit of the motor torque dynamometer, is a flexible, seamless copper bellows such as is employed frequently in thermostats. The ends of the sylphon are closed by brass plates soldered in place, one plate containing a pipe connection for the gages and the other the hardened button through which the load is applied. By this construction it is possible to obtain all the advantages of a closed hydraulic system and to have at the same time a system capable of changes in volume of about the same order as would be obtainable with a cylinder and piston.

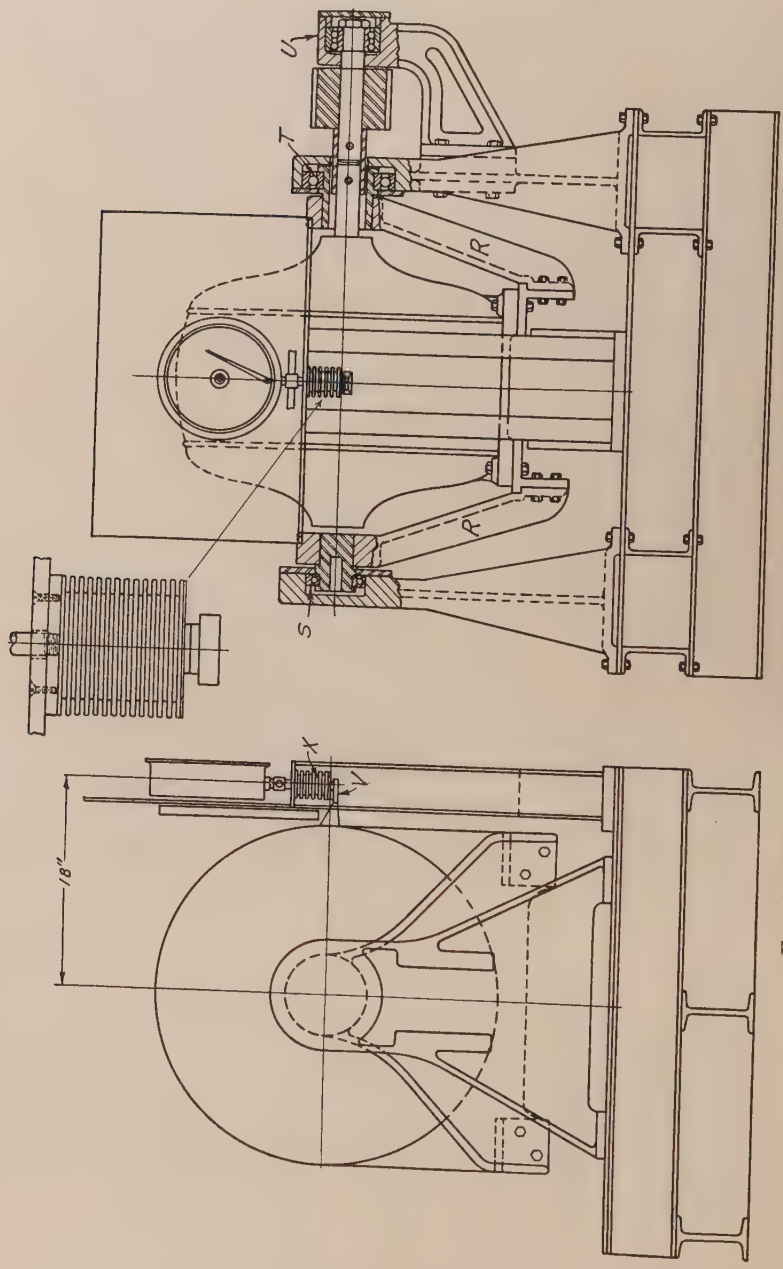


FIG. 3. DETAILS OF MOTOR MOUNTING AND DYNAMOMETER

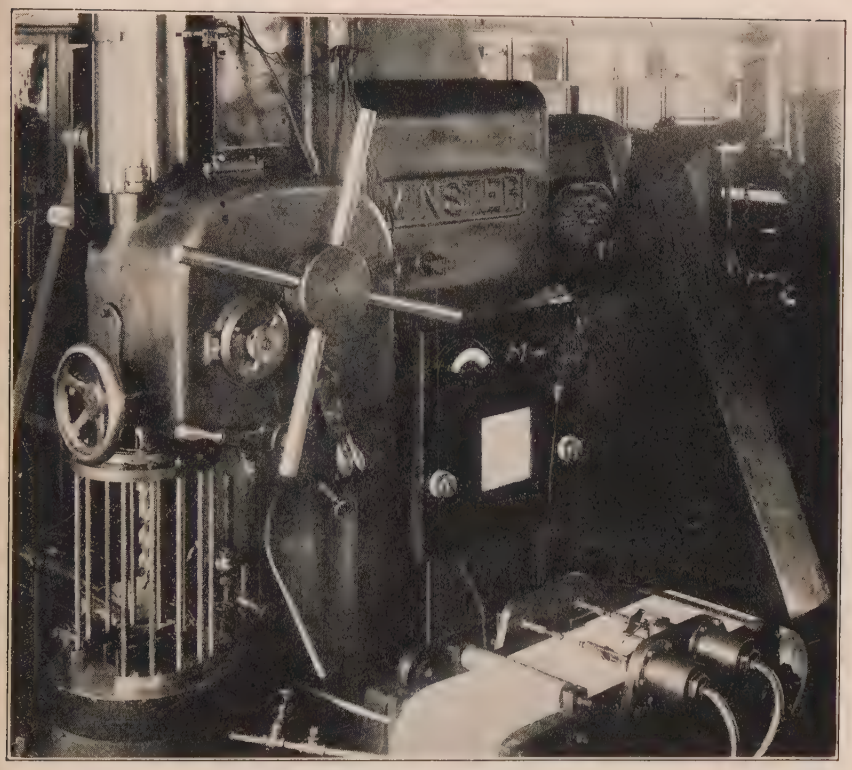


FIG. 4. DRILL DYNAMOMETERS AND RECORDING APPARATUS

6. *Dynamometer.*—The dynamometers* used in measuring the torque and thrust at the drill point are essentially the same as those used throughout the initial investigation.† Considerable modification was necessary, however, before the tests in steel could be completed. Some of the external details of the dynamometers are shown in Fig. 4, while construction details are shown in Fig. 5. Both of these dynamometers are of the hydraulic type, each consisting of a load supporting element and a recording element. The thrust load of the drill is transmitted to the fluid through the medium of the platen *A*, Fig. 5, and a heavy rubber diaphragm. The plate *B*, mounted on a ball thrust bearing on top of the platen, is free to rotate under the action of the drill torque. Such rotation applies a direct load to the sylphon *C* by means of the arm *E* bolted to plate *B* and the plunger *F* which slides on balls in the guide *G*. The fluid used in the torque dynamometer is ordinary

*Designed by T. H. Schance, B.S. in M.E., University of Illinois, 1912
†"An Investigation of Twist Drills," Univ. of Ill. Eng. Exp. Sta. Bul. No. 103, p. 16.

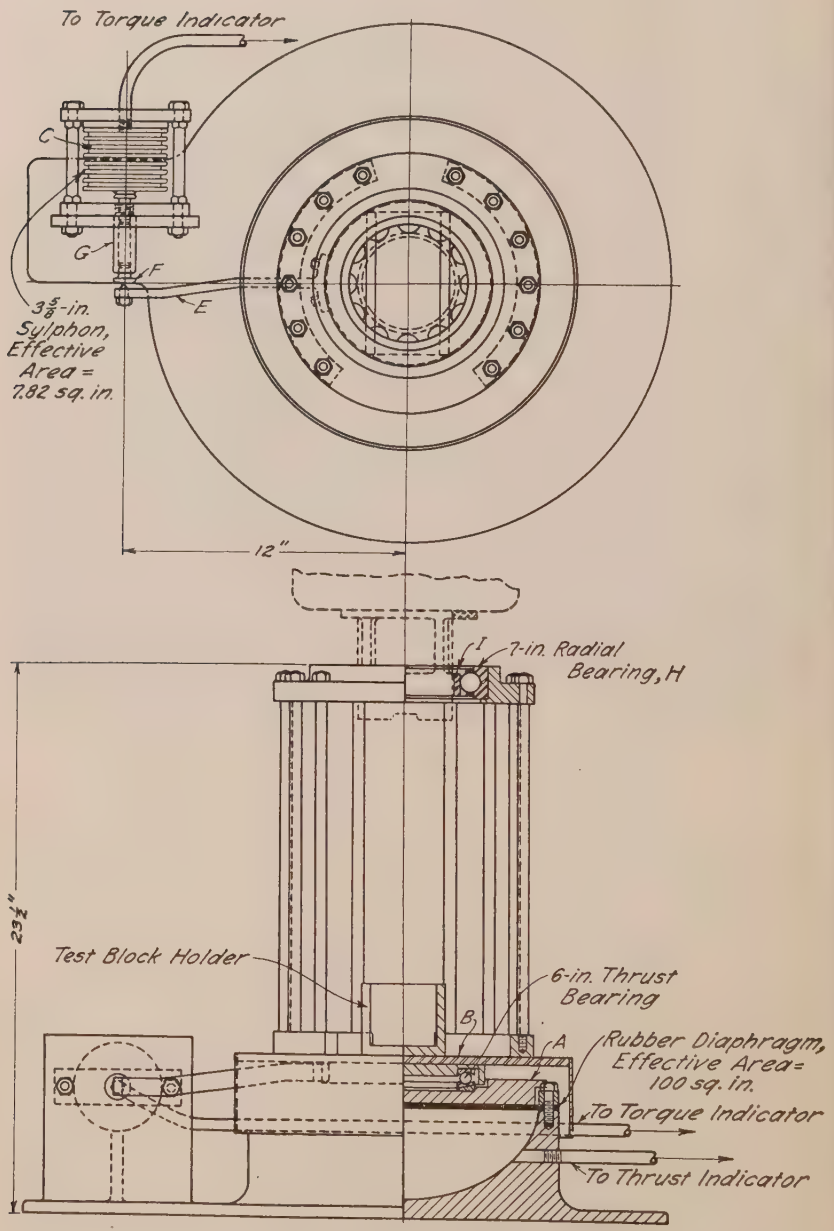


FIG. 5. DRILL DYNAMOMETERS

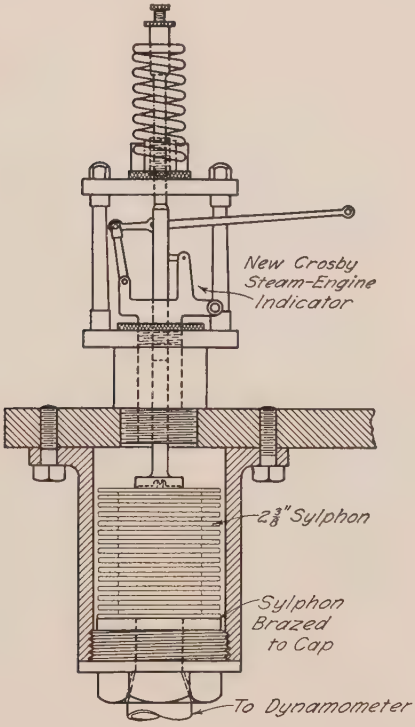


FIG. 6. DETAIL OF THRUST RECORDING INDICATOR

machine oil, but in the thrust dynamometer it was necessary to use castor oil because of the rapid deterioration of rubber diaphragms under the action of mineral oil. Additional support for the rotating table B is secured by means of a cage bolted to the table. A large radial ball bearing H is mounted at the top of this cage and bears on the sleeve I, which is in turn bolted to the frame of the drill press. This sleeve, indicated by the dotted lines in Fig. 5, takes the place of an inner race for the bearing H, and being ground to an accurate fit in the bearing without a ball groove, allows the table B to rotate and move vertically but not horizontally.

The recording element of each dynamometer consists of a modified Crosby steam engine indicator. As may be seen in Fig. 4, these indicators are mounted on a table at the side of the machine and are connected to the load supporting elements of the dynamometers by brass tubing. Details of the construction of the thrust indicator are shown in Fig. 6. Instead of the usual piston and cylinder, the pressure element

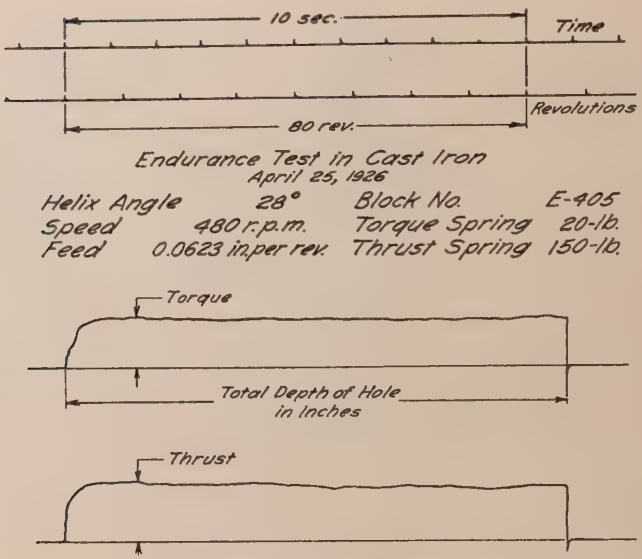


FIG. 7. TYPICAL DYNAMOMETER RECORD

of the indicator consists of a sylphon similar to those used in the motor and drill torque dynamometers. The piston of the indicator is replaced by a brass pad which bears directly on the end plate of the sylphon, and thus any movement of the latter due to pressure changes in the system is communicated to the pencil though the regular linkage. This type of construction, in addition to possessing the advantages of comparatively large volume changes in a closed hydraulic system, also allows easy and rapid change of the measuring element, the indicator spring, so that records with maximum ordinates can be obtained under widely varying load conditions.

The attempt was made in designing the drill dynamometer to obtain a permanent and automatic record of all the factors entering into twist drill performance. With this in view all the recording instruments were arranged on a table at one side of the machine so that simultaneous records of drill torque, thrust, and speed were made on a moving strip of paper. This strip of paper was driven by a cord attached to a drum on the pilot shaft of the drill feed mechanism so that the traverse of the paper was equal to the vertical movement of the drill. The thrust and torque indicators traced their diagrams on this same strip of paper, while the speed record was obtained by means of two electrically controlled pencils, one of which indicated total drill spindle revolutions, and the other, time in seconds. A typical record is shown in Fig. 7.

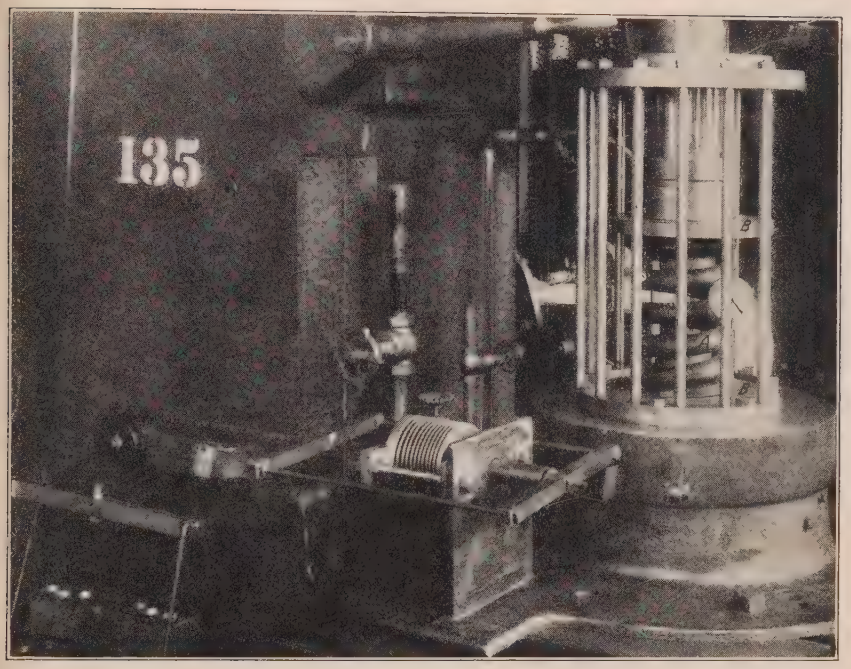


FIG. 8. APPARATUS FOR CALIBRATING DRILL DYNAMOMETERS

7. *Calibration of Dynamometer.*—Due to the size and arrangement of the dynamometers it was necessary to calibrate them in place. The method of doing this is shown in Fig 8. The torque dynamometer was calibrated by means of standardized weights. The weights were supported by a sling, and the vertical force was converted into a horizontal load and applied to the dynamometer sylphon through the medium of a chain passing over a sprocket wheel* and a second sling. In calibrating a given indicator spring it was simply necessary to apply the dead weight in uniform increments and determine the corresponding indicator pencil travel. The procedure in the case of the thrust dynamometer was slightly more involved. Known loads were applied to the table by compressing a spring which had previously been calibrated in a universal testing machine. This spring had a load-deflection rate of approximately 800 lb. per inch and a very uniform calibration curve to over 8000 lb. compressive load. A dead weight of 250 lb. was first placed on the table of the thrust dynamometer and a corresponding base line obtained at the thrust indicator. The dead weight was then replaced

*Since the sprocket was mounted on ball bearings and the movement of the chain was slight, the frictional resistance was considered negligible.

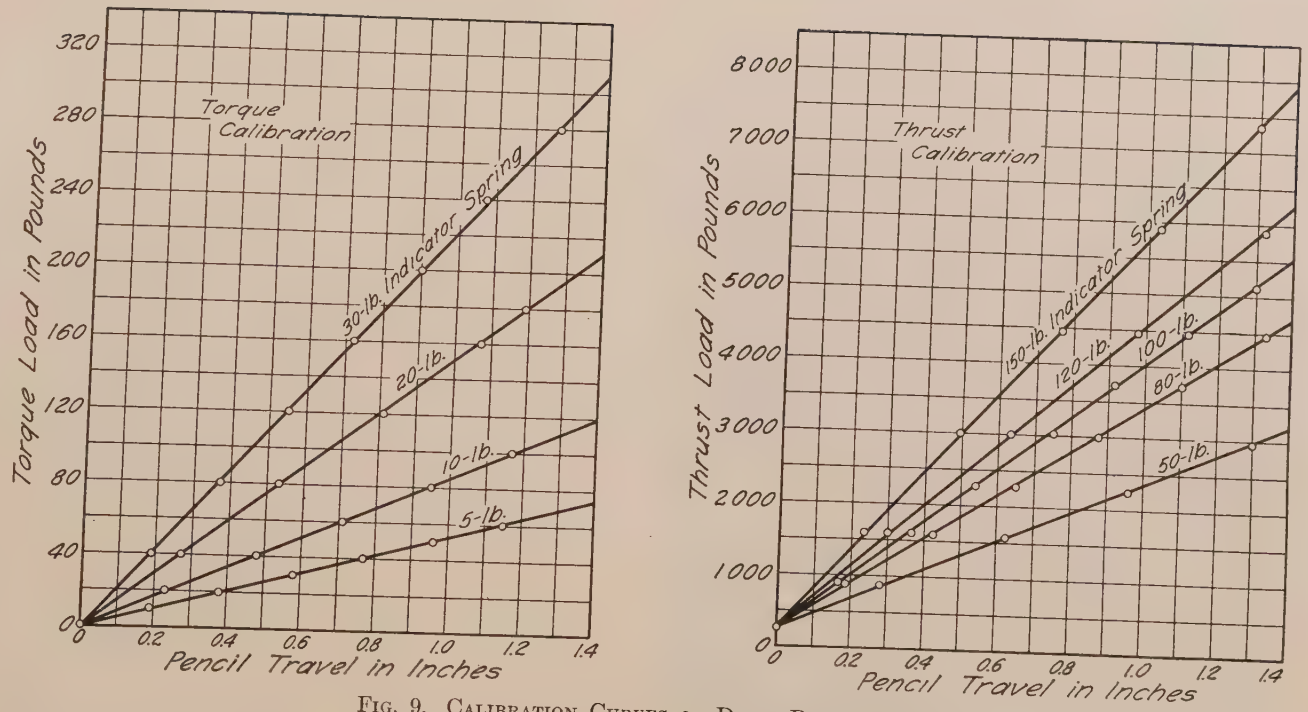


FIG. 9. CALIBRATION CURVES OF DRILL DYNAMOMETERS

by the calibrating spring, this being compressed by feeding down the drill spindle by hand until the pencil of the indicator returned to the base line obtained with the dead weight load. In applying a load to the dynamometer by this method the calibrating spring *A*, Fig. 8, was placed between two plates *B*-*B* which served as reference planes for the measurement of the spring deformation. The actual measurement of the spring compression was made with an Ames dial indicator at three equally spaced intervals around the spring. In order to allow the top plate to tilt slightly and distribute the load over the first coil of the spring, a ball and socket bearing was interposed between the drill spindle and this top plate. The loads were applied to give equal increments of spring compression starting with that corresponding to the 250 lb. load as an initial reading. For each point the pencil travel of the indicator was recorded and the corresponding load obtained from the calibration curve of the loading spring.

In Fig. 9 are plotted curves of indicator pencil travel and load for both dynamometers with several different indicator springs. These curves are straight lines for all springs, and calibrations at frequent intervals during the tests showed practically no variation. From the indicator records made in calibrating the dynamometers, scales were prepared for measuring the test records.

8. *Test Blocks.*—Gray iron test blocks, approximately 2 inches by 6 inches by 12 inches in size, were cast in the University foundry. Uniformity in structure was secured by pouring the blocks used in single tests at one heat, and generally from one large ladle. Blocks were cast in pairs and later broken apart. About $\frac{1}{8}$ in. was planed off the bottom of each block to give a drilling surface. It was possible to drill 10 holes, 5 in. deep, in each block.

Physical properties and chemical composition of blocks used in the endurance tests, typical of all gray cast iron test blocks used, are shown in Table 1.

In determining the influence of helix angle on torque and thrust, care was taken to drill all holes of each series in a single block. To accomplish this result blocks were cut in two lengthwise parallel with the bottom surface, giving three finished surfaces for drilling in each block. In the endurance tests one hole was drilled with each of the seven test drills in each block.

The steel test bars were $1\frac{1}{4}$ in. square and 10 to 12 in. long. Seven different kinds of steel were used in the tests, two carbon steels and five alloy steels. These were selected as being typical steels used in industry. Table 2 shows the physical characteristics and chemical

Table I

Properties of Gray Cast Iron Test Blocks

Heat Number	Physical Properties								Chemical Composition						
	Deflection at Fracture—inches		Transverse Breaking Load in pounds		Brinell Hardness Number				Silicon	Manganese	Phosphorus	Sulphur	Carbon		
	Sample No.		Sample No.		Sample No.		Block						Combined	Graphitic	Total
	1	2	1	2	1	2	Low	High							
6.....	0.1375	0.1100	3047	2318	217	217	149	187	2.35	0.95	0.486	0.100	0.52	2.76	3.28
7.....	0.1180	0.1187	1855	2782	197	197	114	...	2.65	0.49	0.549	0.092	0.50	3.10	3.60
11.....	0.1000	.....	2980	....	192	...	163	170	2.48	0.51	0.513	0.095	0.58	2.86	3.74
14.....	0.0875	0.1000	2915	3445	201	201	159	134	2.42	0.53	0.465	0.093	0.52	2.88	3.40

Table 2

Properties of Steel Test Bars

Manufacturer's Mark	Physical Properties			Chemical Analysis								Type
	Elastic* Limit lb. per sq. in.	Tensile* Strength lb. per sq. in.	Brinell Hardness Number	Carbon	Manganese	Phosphorus	Sulphur	Nickel	Chromium	Vanadium	Silicon	
S.A.E. 1025	40 000	78 000	149	0.22	0.43	0.010	0.043	....	....	....	....	Low-carbon
S.A.E. 1045	60 000	95 000	149	0.37	0.66	0.013	0.025	....	....	....	....	Medium-carbon
S.A.E. 2315	52 000	82 000	134	0.18	0.63	0.008	0.024	3.49	....	....	....	Low-carbon Nickel
S.A.E. 2345	108 000	132 000	163	0.48	0.61	0.011	0.016	3.45	....	....	....	Medium-carbon Nickel
S.A.E. 3130	90 000	108 000	163	0.31	0.65	0.012	0.020	1.47	0.50	....	....	Nickel Chromium
S.A.E. 6145	93 000	120 000	196	0.44	0.77	0.015	.....	....	1.24	0.18	....	Chromium Vanadium
U.M.A. 5	115 000	135 000	202	0.48	0.88	0.014	.....	....	1.05	....	0.13	Chromium

*Figures taken from specifications of Central Steel Co.

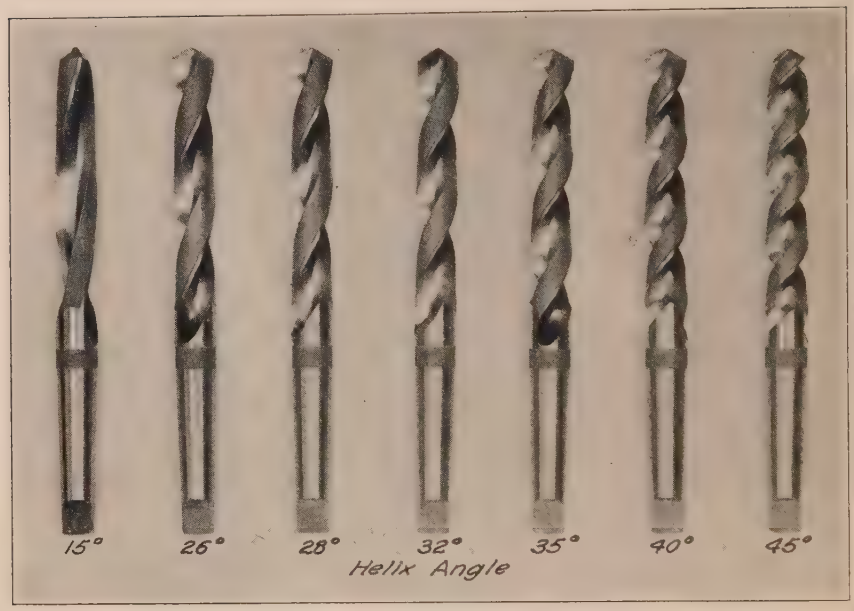


FIG. 10. TEST DRILLS

composition of the various steels. The hardness values and chemical composition shown in the table were obtained from the bars used for drilling; values given for elastic limit and tensile strength are those furnished by the steel manufacturer. The steel test bars were normalized.*

For torque and thrust tests holes were drilled with each drill in all the steels, but in order to avoid unnecessary duplication in the endurance tests, a test of each drill to destruction was made in medium-carbon (S.A.E. 1045) steel only. Comparative machineability tests were made in the various steels with a single drill.

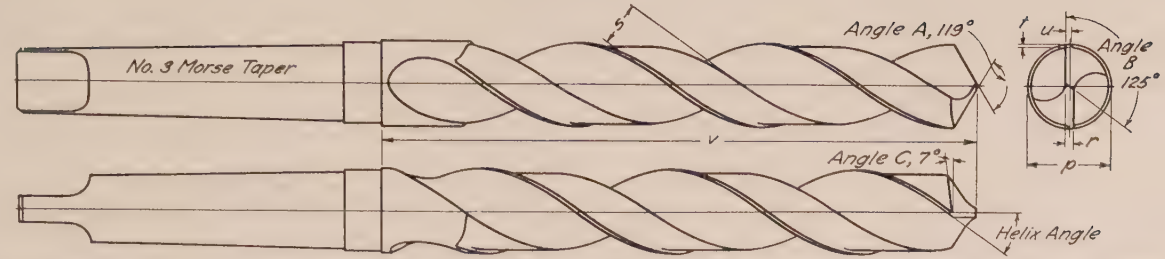
9. *Test Drills.*—One-inch high-speed milled drills were used in these tests in conformity with the practice established in the previous investigation. Drills of this size can be driven at high rates of speed and feed without liability of breakage, and the data obtained are considered to be representative of general drill performance. It is believed that the capacities of drilling machines would be expressed more accurately in terms of performance with inch drills than with 2½-in. or 3-in. drills, the usual practice of manufacturers.

*Normalizing is defined as the heating of steel above the critical range (1300 deg. F. to 1800 deg. F., according to the carbon content) and quenching or air cooling, with the object of breaking down the cementite needles, or large crystals upon which annealing has no effect.

Table 3

Dimensions and Properties of Test Drills

1-in. High Speed Steel Drills



Helix Angle deg.	Length to Shank in.	Diameter, in.		Web Thickness, in.			Lands, in.		Hardness (Scleroscope)		Weight lb.
		At Point	At Shank	At Point	At Shank	At Periph.	Width	Depth	At Point	At Shank	
	v.	p	p′	r	r′	s	u	t			
15	7.20	1.0000	0.9953	0.105	0.102	0.545	0.08	0.03	67	63	1.38
26	7.03	1.0003	0.9970	0.107	0.107	0.618	0.06	0.03	70	68	1.48
28	6.93	1.0000	0.9962	0.100	0.110	0.584	0.07	0.02	69	70	1.48
32	6.87	1.0000	0.9960	0.104	0.104	0.555	0.02	0.03	70	62	1.42
35	7.00	1.0002	0.9960	0.100	0.102	0.515	0.07	0.04	61	37	1.38
40	6.97	1.0000	0.9966	0.100	0.100	0.488	0.05	0.03	65	49	1.38
45	7.02	1.0000	0.9977	0.103	0.108	0.445	0.04	0.03	67	67	1.34

Helix angles constant from point to shank. Cutting angles maintained constant as follows: Point Angle, 119 degrees (Angle A), Edge Angle, 125 degrees (Angle B), Clearance angle, 7 degrees (Angle C).

Seven drills were used throughout the tests (see Fig. 10). They were similar in dimensions except as to helix angles, which varied as follows: 15 degrees, 26 degrees, 28 degrees, 32 degrees, 35 degrees, 40 degrees, 45 degrees. The thickness of the web in all drills was made 0.10 in., and was constant from point to shank. The principal dimensions of the test drills are given in Table 3.

The drills were ground by machine as follows: point angle, 119 degrees, edge angle, 125 degrees, clearance angle, 7 degrees (see sketch accompanying Table 3). Hereafter in the discussion the point angle will be designated as A, the edge angle as B, and the clearance angle as C. With a point angle of 119 degrees the cutting edges of all the drills were straight. The service obtained from the test drills was remarkably uniform and consistent.

III. Description and Results of Tests

10. *Dimensions and Properties of Twist Drills.*—Milled twist drills are furnished to the trade by a score of independent manufacturers located in industrial centers of New England, New York, Pennsylvania, Ohio, and Michigan. With the exception of a small number of new plants brought into existence by the war, twist drills are produced by old established companies specializing in tool manufacture. Individual initiative has governed the development of designs and production methods on lines similar to those followed by the makers of machine tools, although it would appear that the latter had been the first to perceive the advantages of coöperative effort. Notwithstanding the wide distribution of production facilities and the independent character of the industry, twist drills as furnished to the trade are remarkably uniform in appearance and in productive capacity. Without the usual trade marks it would be difficult, in a cursory examination, to identify the drills of different manufacturers and to distinguish one brand from another; and it is doubtful if the usual shop test would show marked differences in their performance. This similarity is but superficial, however, as a careful examination of the commercial brands of drills shows many and pronounced variations in design and details of construction. For purposes of comparison, 17 1-in. milled high speed twist drills from as many manufacturers were accurately measured, and their dimensions and properties are recorded in Table 4. To assist the reader in a critical study of these data, maximum variations in these particulars between drills of various manufacturers are given in Table 5

Although made to rather close limits, the twist drill is not classed as a precision tool. In the shop it is generally employed on roughing

Table 4

Dimensions and Properties of Stock Twist Drills

1-in. High Speed Steel Drills
17 Brands

Drill Symbol	Helix Angle deg.		Length, in.		Diameter, in.			Web Thickness, in.				Lands, in.		Cutting Angle, deg.			Hardness (Scleroscope) at Point	Shank	Weight lbs.	Price in dollars
	Point	Shank	Overall	To Shank	At Point	At Shank	Taper	At Point	At Shank	Taper	At Periph.	Width	Depth	Clearance	Point	Edge				
A.....	31	31	11.35	6.65	1.0003	0.9902	0.0101	0.110	0.197	0.087	0.570	0.06	0.05	13	122	119	63	Solid	1.52	2.81
B.....	36	33	11.35	7.03	0.9997	0.9965	0.0032	0.110	0.182	0.072	0.542	0.06	0.03	19	123	123	66	Welded	1.56	2.50
C.....	25	25	11.20	6.90	1.0010	0.9923	0.0085	0.130	0.231	0.101	0.585	0.10	0.04	19	120	130	64	Solid	1.50	2.50
D.....	28	23	11.25	6.90	0.9984	0.9928	0.0056	0.136	0.229	0.093	0.612	0.09	0.02	10	123	124	69	Welded	1.62	2.90
E.....	28	28	11.47	7.00	1.0003	0.9958	0.0045	0.111	0.236	0.125	0.595	0.07	0.03	5	119	113	65	"	1.58	2.97
*F.....	31	31	10.82	6.47	1.0004	0.9951	0.0053	0.306	0.333	0.027	0.408	0.08	0.03	6	117	112	66	"	1.46	....
G.....	32	27	11.32	6.96	0.9996	0.9971	0.0025	0.114	0.205	0.081	0.550	0.07	0.03	15	120	129	69	"	1.52	2.96
H.....	27	23	11.20	6.88	0.9992	0.9966	0.0026	0.125	0.151	0.026	0.598	0.10	0.04	10	122	119	63	"	1.50	3.13
I.....	30	30	11.18	6.88	0.9987	0.9924	0.0063	0.115	0.208	0.093	0.553	0.08	0.03	12	120	122	70	"	1.52	2.96
J.....	30	30	11.27	6.90	0.9997	0.9969	0.0028	0.121	0.187	0.066	0.599	0.10	0.02	7	119	122	67	"	1.50	2.97
K.....	30	30	11.30	6.90	0.9991	0.9947	0.0044	0.134	0.248	0.114	0.521	0.06	0.03	7	116	119	66	"	1.48	2.97
L.....	23	26	11.25	6.90	0.9997	0.9927	0.0070	0.125	0.265	0.140	0.612	0.07	0.04	28	119	128	63	"	1.62	3.13
M.....	28	25	11.37	6.96	0.9992	0.9953	0.0039	0.122	0.210	0.088	0.553	0.10	0.03	10	120	123	65	"	1.46	2.97
N.....	29	27	11.32	7.05	0.9997	0.9924	0.0073	0.138	0.218	0.080	0.516	0.06	0.04	9	121	117	68	"	1.42	2.97
O.....	28	28	11.26	6.93	0.9993	0.9952	0.0041	0.129	0.241	0.112	0.452	0.05	0.03	11	120	115	68	"	1.48	3.35
P.....	24	24	11.18	6.80	0.9990	0.9928	0.0062	0.124	0.124	0.000	0.665	0.08	0.03	10	117	128	57	"	1.52	2.81
Q.....	29	29	11.48	6.93	0.9997	0.9930	0.0067	0.133	0.217	0.084	0.596	0.06	0.02	9	119	119	63	Solid	1.52	3.13

*Drill of special design, certain dimensions of which are not included in the comparison.

TABLE 5

VARIATIONS IN DIMENSIONS AND PROPERTIES OF STOCK TWIST DRILLS

1-in. High Speed Steel Drills
17 Brands

Item	Maximum Value	Minimum Value	Total Variation
Helix angle, at point, deg	36.	23.	13.
Drill length, overall, in	11.48	11.20	0.28
Drill length, point to shank, in	7.05	6.65	0.40
Drill diameter, at point, in	1.0010	0.9990	0.0020
Drill diameter, at shank, in	0.9969	0.9902	0.0047
Drill diameter, taper from shank to point, in	0.0101	0.0025	0.0076
Web thickness, at point, in	0.138	0.110	0.028
Web thickness, at shank, in	0.265	0.151	0.124
Web thickness, taper from point to shank, in	0.140	0.000	0.140
Web thickness, at periphery, in	0.665	0.452	0.213
Land, width, in	0.10	0.05	0.05
Land, depth, in	0.05	0.02	0.03
Clearance angle, deg	28.	5.	23.
Point angle, deg	123.	117.	6.
Edge angle, deg	130.	115.	15.
Hardness, by scleroscope	70.	57.	13.
Drill weight, lb	1.62	1.42	0.20
Drill price, dollars	3.35	2.50	0.85

Drills with constant helix angle—10, or 59 per cent of total.
Drills with variable helix angle—7, or 41 per cent of total.
Drills with constant web thickness—1, or 5.9 per cent of total.
Drills with variable web thickness—16, or 94.1 per cent of total.

work, as accuracy in hole size is obtained by reaming. Even if made to very accurate limits the almost universal practice of hand grinding would destroy any possible accuracy which could be secured from a drill of exact size. Unquestionably the observed variation in diameter of 0.002 in. between drills of the lot recorded in Table 5 is of trifling importance. Drills made within the recorded limits will not cause trouble from incorrect hole sizes, although some difficulty might arise on certain jobs with drills having the maximum taper (0.01 in.) after they had been in use for some time.

Generally, helix angles have been increased by makers of twist drills during the period between the initial and the present investigation, but drills are still made with helix angles of 23, 24, and 25 degrees. Hand grinding continues to be the prevailing method employed by drill manufacturers for pointing drills, but this practice is no longer universal. To a large extent hardness and durability have been standardized by the employment of high grade steels and scientific methods of heat treat-

TABLE 6
TORQUE OF DRILLS WITH VARIOUS HELIX ANGLES
Drilling Gray Cast Iron

Helix Angle deg.	Torque, ft-lb.			
	Feed, in. per rev.			
	0.0165	0.0256	0.0399	0.0629
15	32.0	43.8	67.7	102.3
26	30.5	40.2	58.1	90.3
32	29.1	36.8	55.6	84.1
35	28.6	35.5	53.0	80.2
40	27.1	33.2	53.4	79.1
45	26.0	32.4	51.0	76.2

TABLE 7
THRUST OF DRILLS WITH VARIOUS HELIX ANGLES
Drilling Gray Cast Iron

Helix Angle, deg.	Thrust, lb.			
	Feed, in. per rev.			
	0.0165	0.0256	0.0399	0.0629
15	1135	2070	3761	5225
26	1167	1682	2939	4750
32	1029	1596	2855	4510
35	1005	1420	2645	4205
40	919	1261	2355	3828
45	824	1158	1831	3278

ment. A variation of over 30 per cent in the price of drills in the open market raises questions relating to production and distribution which cannot be considered here, although they are of economic importance to both manufacturers and users of drills.

11. *Helix Angle Test in Gray Cast Iron.*—In this test a series of holes was drilled in gray cast iron blocks with the object of determining the relative torque and thrust of drills having helix angles of 15, 26, 28, 32, 35, 40 and 45 degrees respectively. An equal number of holes was drilled in the same set of test blocks with each of the drills mentioned, at speeds of 100, 230 and 375 r.p.m., and at feeds of 0.0165, 0.0256, 0.0399, and 0.0629 in. per rev. The readings at a given feed were averaged and this average used as a typical value of torque and thrust for that feed. The results appear in Tables 6 and 7, and are shown graphically in Figs. 11 and 12.

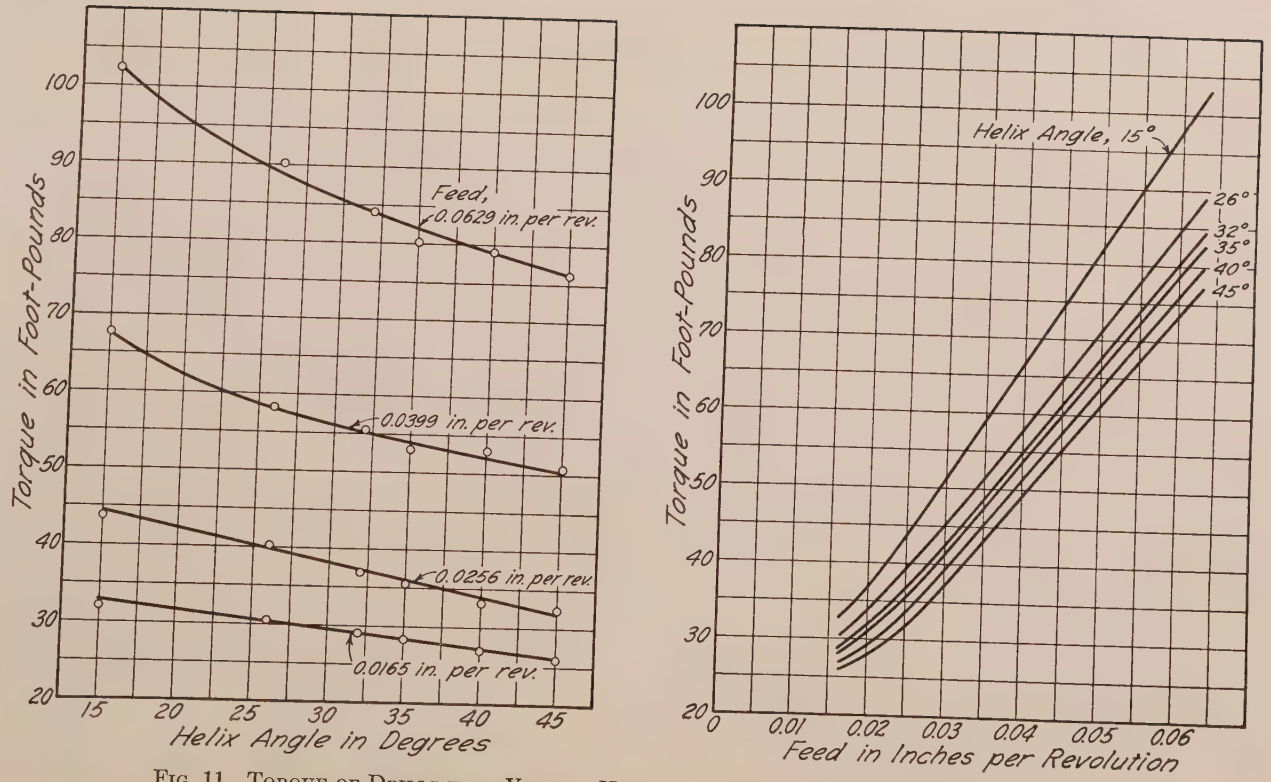


FIG. 11. TORQUE OF DRILLS WITH VARIOUS HELIX ANGLES AND FEEDS, IN GRAY CAST IRON

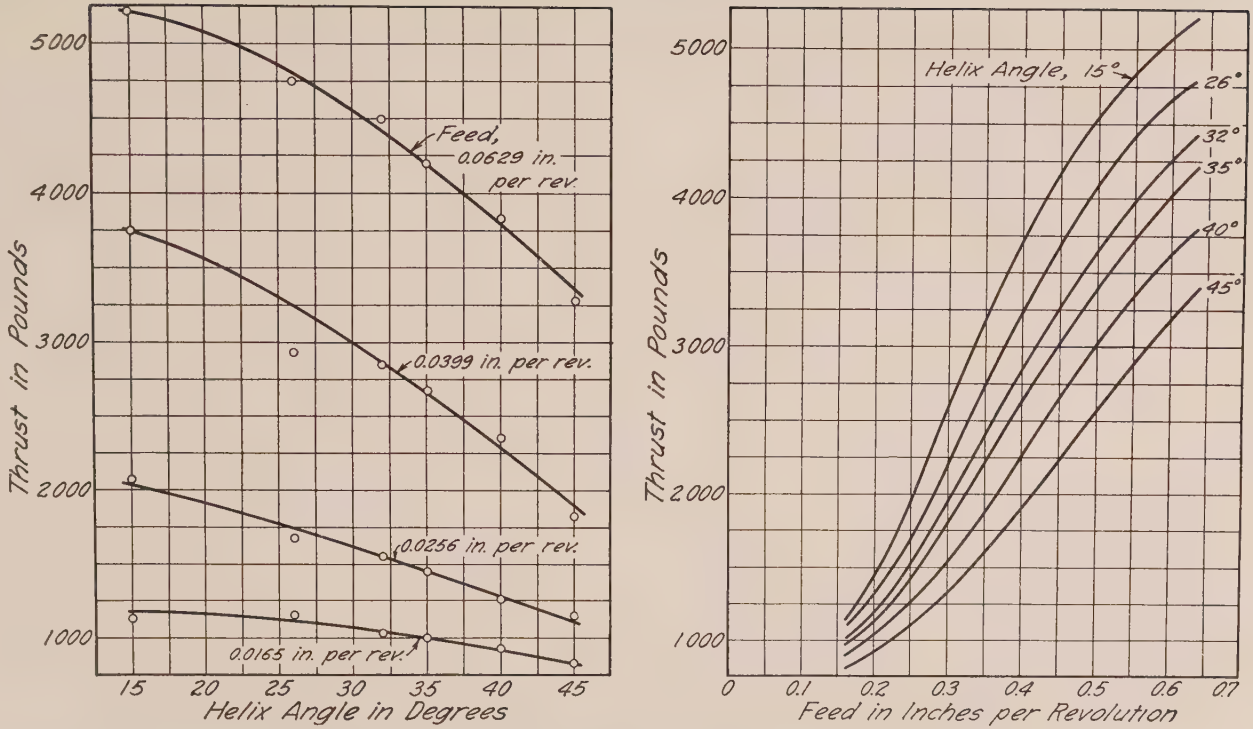


FIG. 12. THRUST OF DRILLS WITH VARIOUS HELIX ANGLES AND FEEDS, IN GRAY CAST IRON

Referring to Fig. 11, it is apparent that there is a direct relation between the helix angle of the drill and the torque required to remove the chip. At all the feeds employed the torque decreased as the helix angle of the drill increased, the decrease being more pronounced at the highest drilling rate. As the clearance angle was maintained at 7 degrees on all drills used in the test, changes in helix angle result in equal changes in lip angle at the periphery of the drill, as follows:

Helix Angle, Degrees	Lip Angle, Degrees
15	68
26	57
28	55
32	51
35	48
40	43
45	38

Thus an increase in helix angle from 15 to 45 degrees, a total of 30 degrees, is accompanied by a decrease of 30 degrees in the lip angle at the periphery of the drill. Larger helix angles mean smaller lip angles and correspondingly sharper cutting edges. This explains why the work of removing the chip decreases as the helix angle is increased. At a feed of 0.0629 in. per rev. the torque decreases from 102.3 ft. lb. for a helix angle of 15 degrees, to 76.2 ft. lb. for a helix angle of 45 degrees, a decrease of 25.5 per cent. Drills with the traditional helix angle of 26 degrees require 18.5 per cent greater torque than those with a 45-degree helix angle at this drilling rate in gray cast iron. A comparison of the torque of test drills at various feeds is shown in Fig. 11.

If power consumption were the only factor to be considered there would be no reason for making drills with helix angles less than 45 degrees, even for use in gray cast iron. Lip angles of cutting tools for gray cast iron usually are much greater than those found in similar tools for cutting steel, since a blunter form is necessary to prevent crumbling of the cutting edge. Gray cast iron is of a brittle structure and in cutting it breaks off in small particles, throwing the pressure of the chip close to the cutting edge. This condition, coupled with the higher cutting speeds used, makes it necessary to provide tools with blunter lip angles for gray cast iron than for steel. Tradition, therefore, is against small lip angles for cutting gray cast iron, and doubtless this is largely responsible for the practice of making high speed twist drills with large lip angles, although such lip angles are a relic of the age of carbon steel. Taylor's recommendation to use "the keenest cutting angle which is free from danger of spalling" for lathe tools unquestionably

FIG. 13. CHIPS FROM DRILLS WITH 26- AND 35-DEGREE HELIX ANGLES, IN GRAY CAST IRON

is applicable to twist drills also. That the action of the two tools is dissimilar should not cause confusion, as the ultimate functions of both are identical, i.e., reduction of mass by removing a chip of definite dimensions at a predetermined rate

In practice, the chips from drills of different helix angles tell much about the action of the cutting lip, and indirectly show why less torque is necessary to remove chips with drills of larger helix angles. A typical collection of gray cast iron chips from drills with 26-degree and 35-degree helix angles, respectively, operating in the same block and at the same drilling rate, is shown in Fig. 13. From the 26-degree angle drill the chips are splinters of metal broken or pushed off the block by the blunt cutting edge. In sharp contrast are the shavings of iron cut from the block by the 35-degree angle drill with its more acute lip angle. This practical evidence of the superior cutting qualities of drills with lesser lip angles serves to confirm the results of the tests with the dynamometer which already have been discussed.

The effect of flute contours on torque has not yet been investigated but there is some evidence at hand to support the belief that it is measurable, and is a subject worthy of further attention. In the initial in-

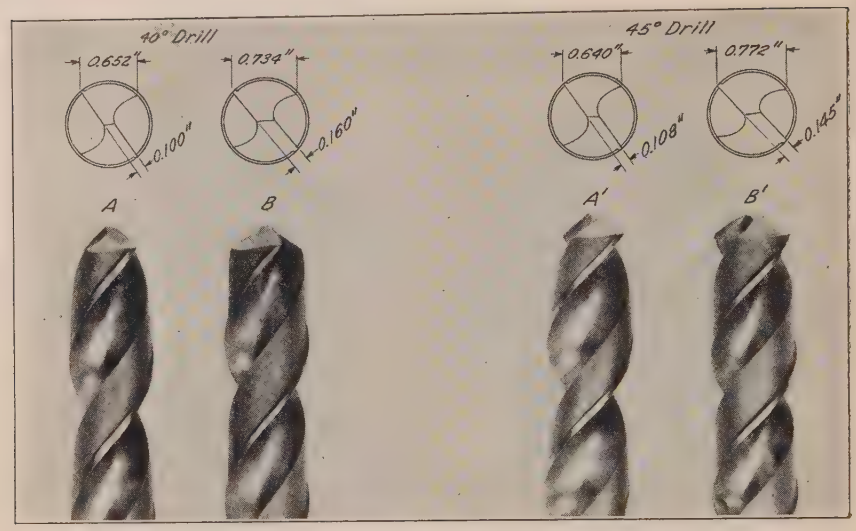


Fig. 14. Comparison of Drills of Different Design

vestigation* the lowest values of torque in drilling gray cast iron were found with the 35-degree helix angle drill, slightly higher readings being registered by drills of 40- and 45-degree helix angles. These results were not duplicated in the present test using drills of the same helix angles but with considerably larger flutes and thinner chisel edges. At all drilling rates in both gray cast iron and steel the torque readings of the 40- and 45-degree helix angle drills invariably were lower than those of the 35-degree helix angle drill. Contrasts in the design and dimensions of the particular drills mentioned are shown clearly in Fig. 14. Drills of the present investigation are marked A and A′, those of the initial investigation are designated by the letters B and B′. The conclusion seems reasonable, although not yet definitely supported by test results, that the larger flutes serve to reduce torque by improving the cutting action of the drill.

Thrust on the end of the drill is influenced by a number of factors including helix angle, width of chisel edge (web thickness), point angle, and clearance angle. As the chisel edge operates with a scraping and not a cutting action, it virtually crushes a cylinder of metal having a diameter equal to its width and a length corresponding to the depth of the hole. Approximately from 60 to 70 per cent of the thrust on the drill of usual design is set up by the chisel edge.† If this edge is of unnecessary width,

*See "An Investigation of Twist Drills," Univ. of Ill. Eng. Exp. Sta. Bul. 103.
†See "An Investigation of Twist Drills," Univ. of Ill. Eng. Exp. Sta. Bul. 103, p. 58.

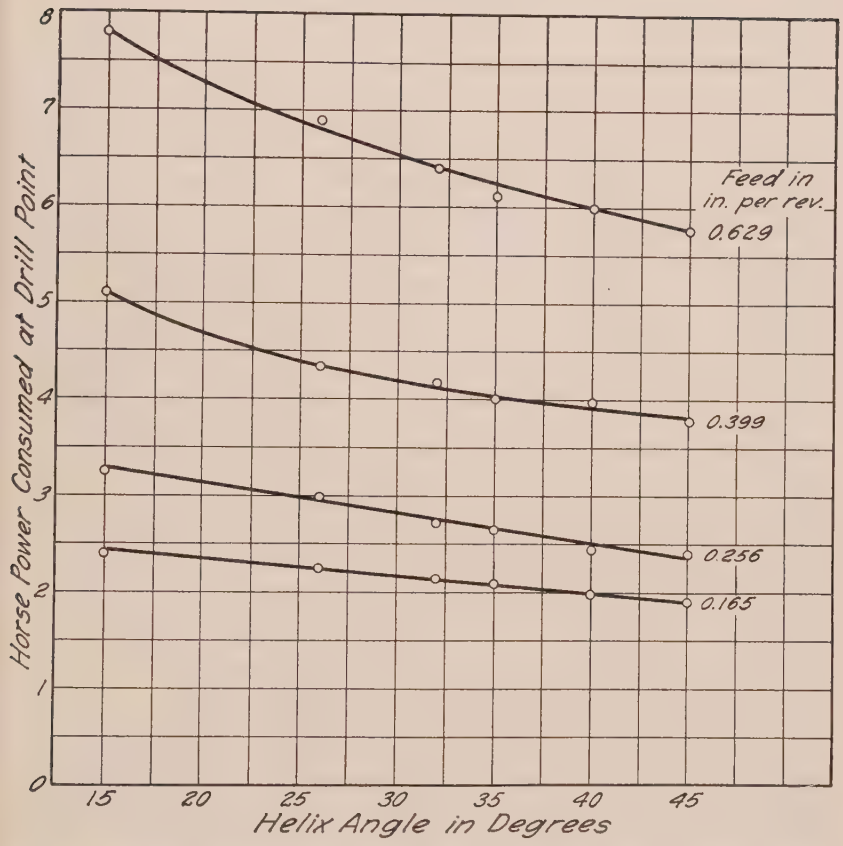


FIG. 15. POWER CONSUMPTION AT THE DRILL POINT OF DRILLS WITH VARIOUS HELIX ANGLES, IN GRAY CAST IRON

excessive thrust results, and an abnormal load is thrown upon the drill and the drilling machine. Helix angle has a marked effect on thrust in drilling gray cast iron, as indicated by the test results shown in Table 7, and in Fig. 12. Referring to the latter, it is observed that the thrust decreases progressively as the helix angle is increased. Obviously, the decrease is most pronounced at the heaviest drilling rate. At a feed of 0.0629 in. per rev. there is a decrease in thrust from 5225 pounds with the 15-degree helix angle drill to 3278 pounds with the 45-degree helix angle drill, a total of 1947 pounds, or 37.2 per cent. Reduction in thrust with the 35-degree helix angle drill over that with the 26-degree helix angle drill is approximately 12 per cent. By a logical combination of helix angle and web thickness it is possible to reduce thrust to a minimum, and thus improve the cutting qualities of the drill.

TABLE 8

POWER CONSUMPTION OF DRILLS WITH VARIOUS HELIX ANGLES

Drilling Gray Cast Iron

Helix Angle, deg.	Total H. P. at Drill Point			
	Feed, in. per rev.			
	0.0165	0.0256	0.0399	0.0629
15	2.40	3.26	5.10	7.79
26	2.25	2.98	4.35	6.89
32	2.15	2.73	4.17	6.41
35	2.10	2.64	4.01	6.12
40	1.99	2.46	3.99	6.01
45	1.91	2.40	3.80	5.77
	H.P. Consumption due to Torque			
15	2.38	3.21	4.95	7.47
26	2.23	2.94	4.24	6.60
32	2.13	2.69	4.06	6.14
35	2.09	2.60	3.91	5.86
40	1.98	2.43	3.90	5.78
45	1.90	2.37	3.73	5.57
	H.P. Consumption due to Thrust			
15	0.018	0.051	0.145	0.320
26	0.019	0.042	0.113	0.290
32	0.016	0.040	0.110	0.270
35	0.016	0.035	0.102	0.260
40	0.015	0.031	0.091	0.230
45	0.013	0.029	0.071	0.200

For practical purposes, the power consumption at the drill point when drilling gray cast iron or steel may be computed from the torque alone, since the power required to feed the drill is but a small portion of the total power. At a feed of 0.0629 in. per rev., 3.4 per cent of the total power used is due to thrust with the 45-degree helix angle drill, while at a feed of 0.0165 in. per rev. with the same drill less than 0.7 per cent of the power used was accounted for by thrust. For the 26-degree helix angle drill the power loss due to thrust at these drilling rates is 4.2 per cent and 0.84 per cent respectively. The relative power consumption of different drills at various feeds, in gray cast iron, is shown graphically in Fig. 15, and the corresponding figures are presented in Table 8. At all the drilling rates employed in the test on gray cast iron, power consumption at the drill point decreased as the helix angle was increased from 15 to 45 degrees, confirming the conclusion that twist drills with smaller lip angles require less power to remove the chip, as is the case with other metal cutting tools also.

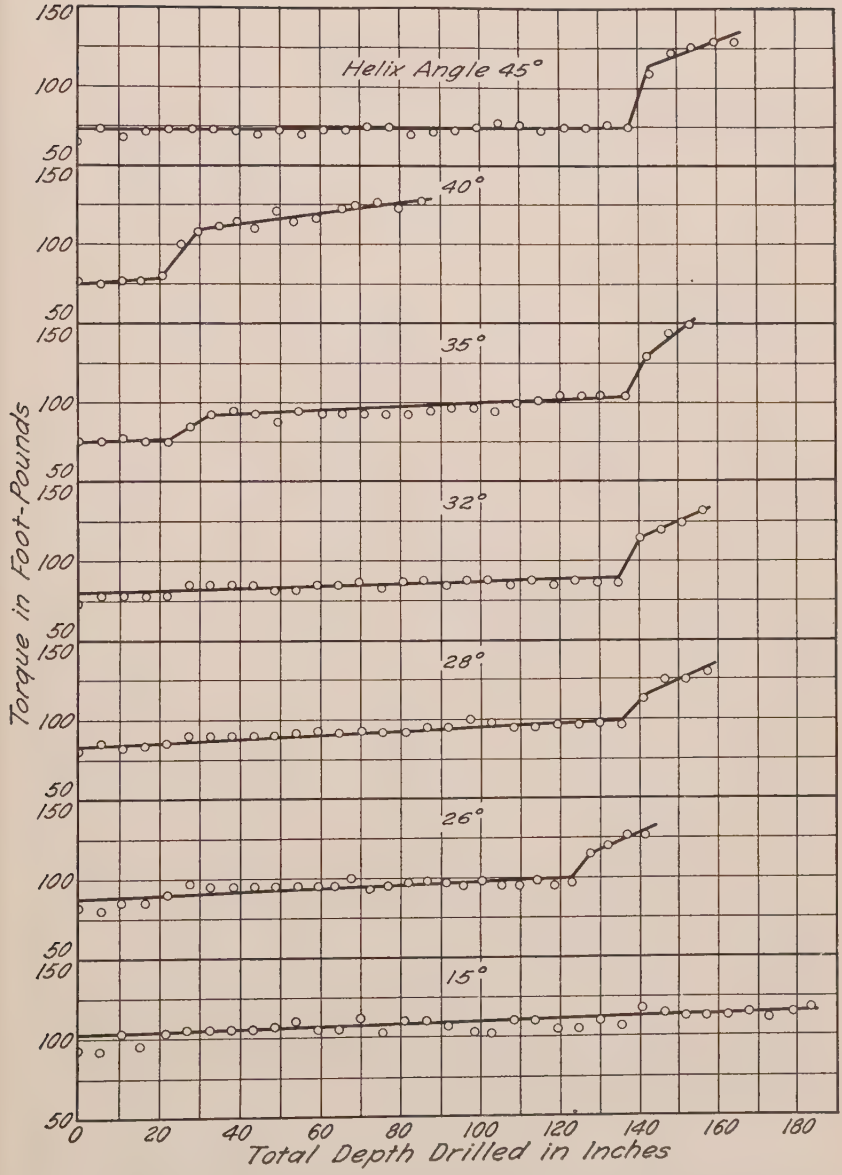


FIG. 16. TORQUE OF DRILLS WITH VARIOUS HELIX ANGLES IN ENDURANCE TEST, IN GRAY CAST IRON

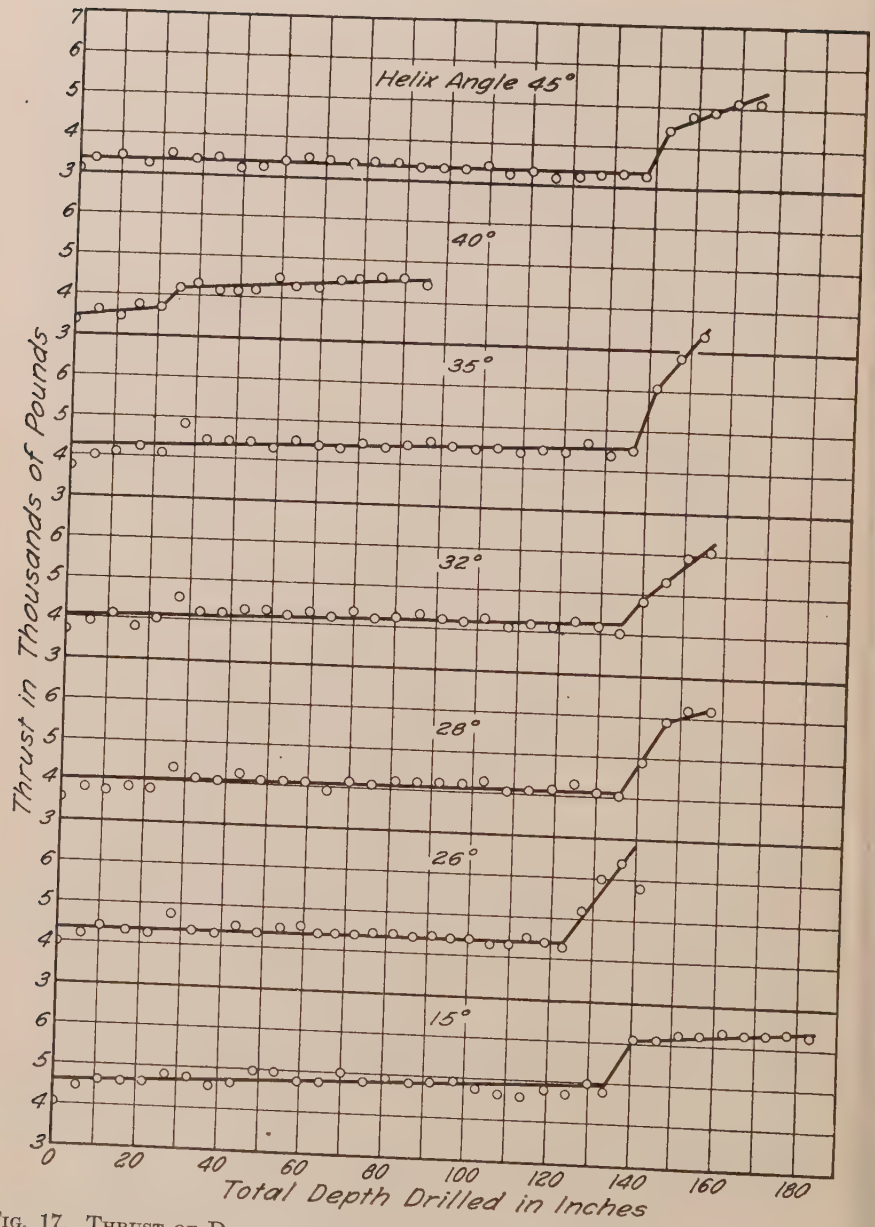


FIG. 17. THRUST OF DRILLS WITH VARIOUS HELIX ANGLES IN ENDURANCE TEST, IN GRAY CAST IRON

TABLE 9

RELATIVE ENDURANCE OF DRILLS WITH VARIOUS HELIX ANGLES

Drilling Gray Cast Iron
Speed, 500 r.p.m. Feed 0.0623 in. per rev.

Helix Angle deg.	Total Depth Drilled, in.	Per cent Increase at Depth Indicated	
		In Torque	In Thrust
15	135	15.0	18.5
26	123	18.3	7.5
28	135	21.2	14.3
32	135	19.2	9.4
35	137	40.0	21.3
40	21	3.9	1.0
45	138	15.4	6.4

12. *Endurance Test in Gray Cast Iron.*—The relative endurance of drills with helix angles of 15, 26, 28, 32, 35, 40, and 45 degrees, respectively, was determined by driving each of the drills to destruction under identical operating conditions. All drills were ground by machine according to the specifications in Table 3. A drilling rate in excess of that used in customary practice was used to accentuate, if possible, differences in the various drills. This rate was: spindle speed, 500 r.p.m., or 131 ft. per min. at the drill periphery; feed, 0.0623 in. per rev., or a penetration of 31 in. per min. The outside corners of the drills were not rounded to secure maximum endurance, as the test was planned to reveal the relative stamina of drills having widely diverging lip angles, and it was believed that this aim would be furthered by allowing the most vulnerable point in the cutting edge to remain unchanged. Although the test was continued to absolute destruction, the factor of endurance in drilling gray cast iron was measured in terms of depth drilled before sudden increases in torque and thrust indicated the beginning of the final breakdown in the cutting edge. The results of this test are shown graphically in Figs. 16 and 17. It is apparent from the curves in these figures that the cutting edge of a high speed drill is subject to a small but progressive deterioration for a certain period of service, and that eventually a critical condition develops which leads to rapid and complete failure. This critical point for each of the drills is shown clearly by the breaks in the curves of torque and thrust in Figs. 16 and 17. Neglecting the eccentric behavior of the 40-degree helix angle drill, due probably to uncontrolled test conditions, the results show that the endurance of drills in gray cast iron is not influenced materially by the factor of helix angle. The

TABLE 10

RELATIVE PERFORMANCE OF 26- AND 45-DEGREE HELIX ANGLE DRILLS

Drilling Gray Cast Iron
Speed 500 r.p.m. Feed 0.0623 in. per rev.

Factor	(1) Helix Angle 26-deg.	(2) Helix Angle 45-deg.	Difference between (2) and (1)
Lip angle, deg	57.0	38.0	−19.0
Inches drilled	123.0	138.0	+15.0
Torque, at start, ft-lb	82.0	65.0	−17.0
Torque, at close, ft-lb	97.0	75.0	−22.0
Increase in torque, per cent	18.3	15.4	− 2.9
Thrust, at start, lb	4000.0	3100.0	−900.0
Thrust, at close, lb	4300.0	3300.0	−1000.0
Increase in thrust, per cent	7.5	6.4	− 1.1

number of inches drilled by each test drill before the critical period of the cutting developed is given in Table 9. An examination of these figures reveals the interesting fact that the endurance of the 45-degree helix angle drill with a lip angle of 38 degrees was appreciably greater than that of the 26-degree helix angle drill with a lip angle of 57 degrees. As the latter drill represents traditional practice in drill manufacture, the large lip angle being considered necessary to insure endurance, it is instructive to compare in some detail its performance with that of a drill having a more acute lip angle, as shown in Table 10. The conclusion is obvious from the results therein presented that in high speed twist drills lip angle is not the only factor affecting endurance when drilling gray cast iron. Reduction in the lip angle reduces the torque and thrust required for drilling, indicating freer cutting action and less heat generated in removal of the chip. Apparently the heat reduction from this cause is considerable as otherwise the endurance of the high-angle twist drills is not explainable.

The appearance of the test drills at the close of the endurance test in gray cast iron is shown in Fig. 18. It will be observed that while the cutting edges of all the drills are intact, although dull, the sharp corners at the periphery are badly burned. After the critical condition at the sharp corner is reached the high-angle twist drills break down more rapidly at a heavy drilling rate than those with smaller helix angles. At the critical point the former are no longer cutting freely at the periphery, and they break down rapidly at the corner from overheating. Since the sharp corner is the weakest portion of the cutting edge, endurance may be increased by rounding it on the grinder to a definite curve.

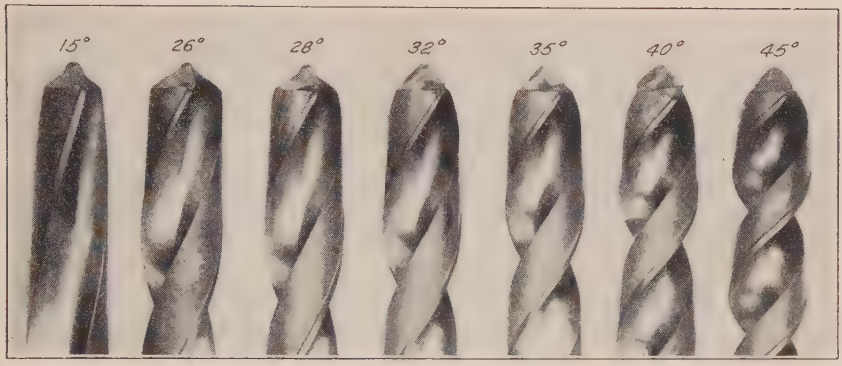


FIG. 18. CONDITION OF TEST DRILLS AT CLOSE OF ENDURANCE TEST IN GRAY CAST IRON

The excellence of the modern high speed twist drill was demonstrated during the endurance test in gray cast iron. Through misadjustment of the test block when drilling with the 45-degree helix angle drill, a "run-in" hole was drilled as shown in Fig. 19. The drill broke close to the shank at a depth of $1\frac{7}{8}$ in., the point being $\frac{7}{16}$ in. out of line with the center of the spindle. As a twist drill is not designed to resist large stresses resulting from cross bending, this minor occurrence in the investigation illustrates in a striking manner the unusual strength of high speed steel when heat treated to secure toughness and hardness.

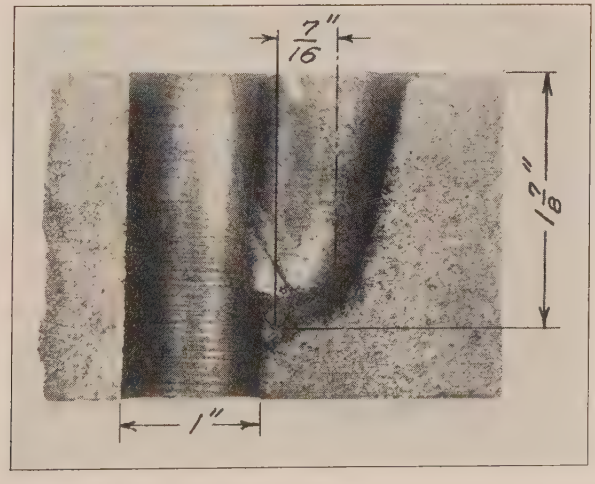


FIG. 19. SECTION OF GRAY CAST IRON TEST BLOCK SHOWING RUN-IN HOLE

13. *Summary of Results of Tests in Gray Cast Iron.*—The following observations were made during the tests:

(1) Torque and thrust decreased progressively as the helix angle was increased from 15 degrees to 45 degrees; both were lowest when the helix angle was 45 degrees.

(2) At the highest rate of feed used, 0.0629 in. per rev., increasing the helix angle from 15 to 45 degrees resulted in reducing the torque by 25.5 per cent, and the thrust by 37.2 per cent.

(3) Thrust was influenced most by helix angle, and by the thickness of the web. Test drills with web thickness of 0.1 in., constant from point to shank, gave entire satisfaction at all speeds and feeds.

(4) Chip removal when drilling holes 5 in. deep was effective with drills having constant helix angles from point to shank.

(5) Savings in power consumption at the drill point by increasing the helix angle from 15 to 45 degrees ranged from 2 to 26 per cent, at drilling rates of 0.0165 and 0.0629 in. per rev. respectively.

(6) From 95 to 99 per cent of the power consumption at the drill point was due to torque, the remainder resulting from thrust.

(7) Drill endurance was not influenced by changes in helix angle from 26 to 45 degrees, inclusive, at normal drilling rates.

14. *Helix Angle Test in Steel.*—This test was planned to determine the relative torque and thrust of drills having helix angles of 15, 26, 28, 32, 35, 40, and 45 degrees respectively, when drilling at rates ordinarily used in practice, in typical carbon and alloy steels used in industry. The test procedure was the same as employed in the corresponding test in gray cast iron except that the drills were cooled by a heavy stream of water. A series of five holes was drilled in each of the steels listed in Table 2, at a speed of 300 r.p.m. and at feeds of 0.0131, 0.0206, and 0.0320 in. per rev. Each set of readings at a given feed was averaged and the resulting figure used as a typical value of torque and thrust at that feed. The results are presented in Table 11, and are shown graphically in Figs. 20 and 21.

From a comparison of the torque curves for gray cast iron (Fig. 11) and for steel (Fig. 20) it is obvious that the effect of helix angle on torque is, in general, the same when drilling either of these metals. Increasing helix angles from 15 to 45 degrees serves to reduce the torque required for drilling either metal at all the drilling rates employed in the test. An equivalent reduction in torque is observed for gray cast iron and chromium nickel steel (S.A.E. 3130), although the actual torque values

Table 11

Torque and Thrust of Drills with Various Helix Angles

Drilling Various Steels

Helix Angle deg.	Feed, in. per rev.	Grades of Steel						
		S.A.E. 1025	S.A.E. 1045	S.A.E. 2315	S.A.E. 2345	S.A.E. 3130	S.A.E. 6145	U.M.A. 5
		Torque in Foot-Pounds						
15	0.0131	66.2	54.8	63.6	62.2	53.4	60.4	62.8
	0.0206	99.0	81.2	110.2	99.4	78.8	96.8	99.6
	0.0320	110.0	125.0	.....	....	....	....	....
26	0.0131	51.2	48.6	52.4	53.0	48.4	54.8	54.4
	0.0206	78.4	73.2	77.0	86.2	72.8	75.6	80.6
	0.0320	112.4	103.0	139.8	141.6	103.6	120.6	140.0
28	0.0131	52.0	50.6	51.0	54.8	48.6	54.8	57.8
	0.0206	75.6	75.0	77.6	83.2	73.2	74.6	80.0
	0.0320	106.8	99.8	126.6	137.0	105.6	111.0	136.5
32	0.0131	48.4	45.6	47.4	51.4	46.4	49.6	51.4
	0.0206	69.2	68.8	68.6	78.4	68.8	73.4	75.0
	0.0320	98.4	97.4	107.4	129.2	99.8	104.4	122.4
35	0.0131	44.6	43.6	46.0	48.2	43.8	48.8	49.0
	0.0206	64.8	69.4	67.4	74.0	67.4	70.8	76.2
	0.0320	98.0	97.0	103.2	122.0	98.6	104.6	117.6
40	0.0131	41.8	42.6	43.4	47.6	42.4	48.0	49.2
	0.0206	60.8	67.4	67.0	72.8	62.4	70.2	73.8
	0.0320	93.8	94.4	96.2	109.6	95.4	101.4	111.2
45	0.0131	41.0	45.8	43.2	50.8	44.8	48.8	48.2
	0.0206	56.6	65.8	67.0	73.4	61.6	68.0	71.4
	0.0320	89.2	94.4	95.6	109.4	92.4	102.4	106.0
		Thrust in Pounds						
15	0.0131	1950	1738	1908	1974	1740	1918	1964
	0.0206	2590	2430	3300	5875	3100	5510	5890
	0.0320	5475	4420	....	....	....	....	....
26	0.0131	1628	1778	1716	1910	1834	2038	2084
	0.0206	2460	2600	2640	3970	2480	2910	3020
	0.0320	3620	3770	5080	6480	3500	4320	5500
28	0.0131	1638	1776	1744	1888	1758	1930	2030
	0.0206	2390	2600	2500	3920	2570	2730	3000
	0.0320	3370	3520	4540	5990	3400	4400	5600
32	0.0131	1598	1676	1656	1914	1696	1896	1956
	0.0206	2110	2370	2270	3230	2240	2590	2760
	0.0320	3040	3530	3860	5690	3290	4060	4880
35	0.0131	1486	1610	1518	1794	1518	1794	1894
	0.0206	1950	2280	2130	3220	2180	2520	2610
	0.0320	3220	3250	3590	4950	3150	3980	4560
40	0.0131	1354	1490	1404	1684	1496	1660	1704
	0.0206	1790	2210	1980	2810	1980	2340	2440
	0.0320	2560	3050	3080	4480	2920	3550	4030
45	0.0131	1180	1350	1290	1686	1336	1556	1590
	0.0206	1640	1840	1650	2330	1700	2060	2110
	0.0320	2190	2710	2700	3800	2760	3310	3510

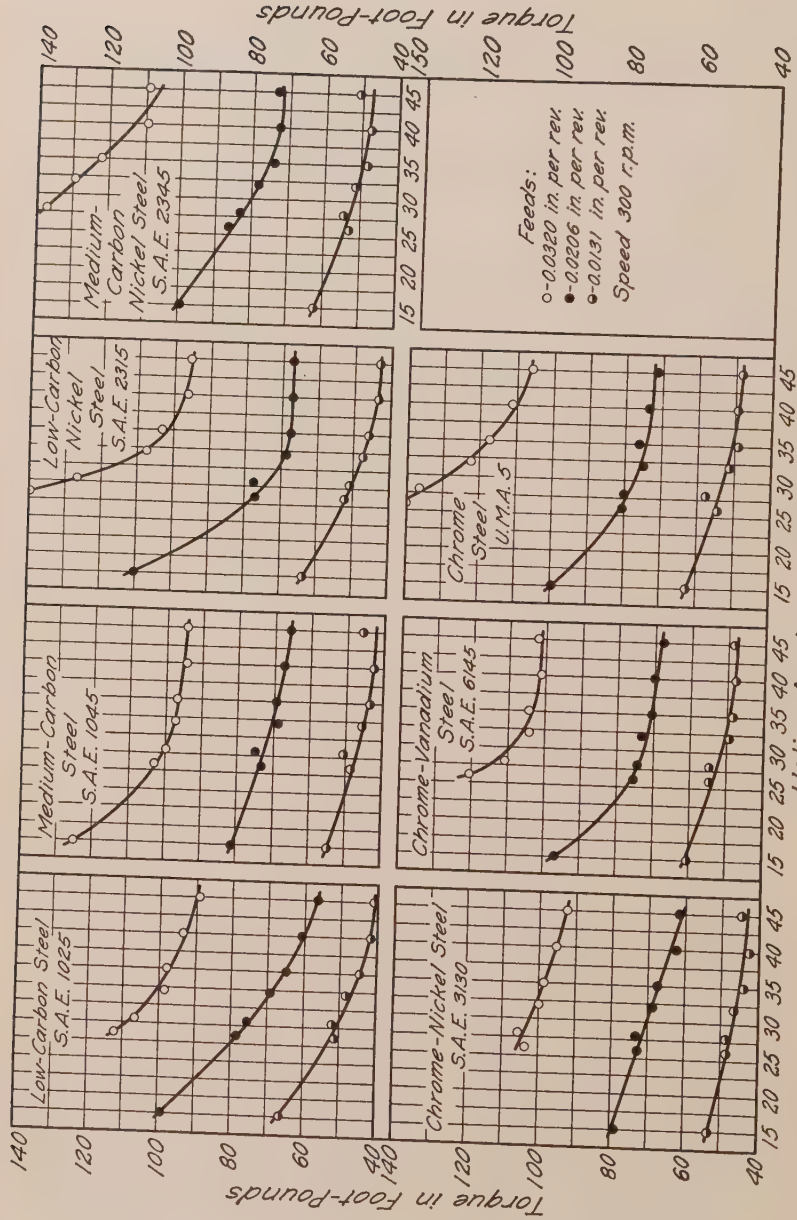


Fig. 20. Torque of Drills with Various Helix Angles, in Seven Grades of Steel

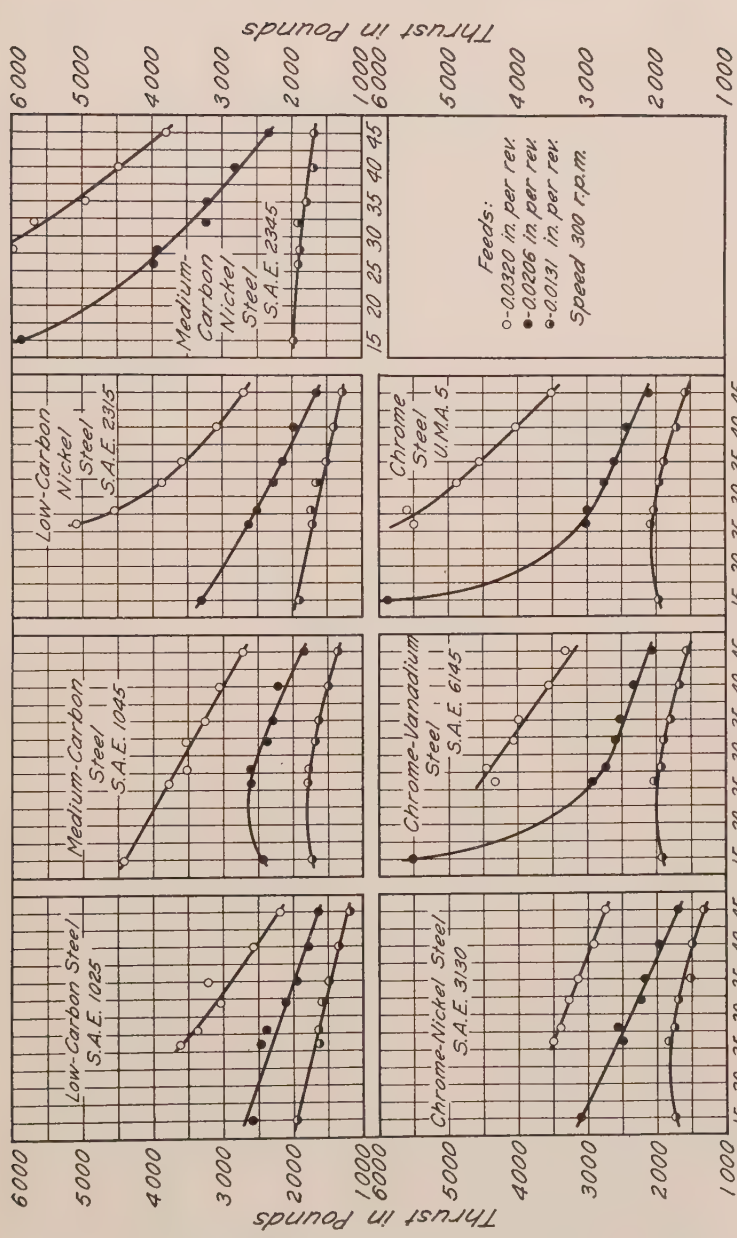


FIG. 21. THRUST OF DRILLS WITH VARIOUS HELIX ANGLES, IN SEVEN GRADES OF STEEL

are not the same. For the remaining steels the reduction in torque due to increasing the helix angle through the range indicated is much greater than in the case of gray cast iron or chromium nickel steel.

It was assumed at the beginning of the test, in the absence of exact information on the subject, that increasing the helix angle would result in reductions in torque for the steels used, approximately in proportion to their hardness. The correctness of this assumption was not confirmed by the test. On the contrary, it was found that the effect on torque of increasing the helix angle was not uniform for steels of different chemical composition, and, further, that there appeared to be no definite relation between hardness and torque. Proof of the first statement is seen in the widely divergent torque curves in Fig. 20. For the purpose of a quantitative comparison, the per cent reduction in torque resulting from an increase in the helix angle from 26 to 45 degrees for each of the test steels is tabulated below (feed 0.0320 in. per rev., speed 300 r.p.m.):

Steel, grade			Per cent Reduction
Low-carbon	S.A.E.	1025	20.7
Medium-carbon	S.A.E.	1045	8.3
Low-carbon Nickel	S.A.E.	2315	31.6
Medium-carbon Nickel	S.A.E.	2345	22.8
Chromium Nickel	S.A.E.	3130	10.8
Chromium Vanadium	S.A.E.	6145	15.1
Chromium	U.M.A.	5	24.3

It is obvious from these values that increasing the helix angle of the drill lowers the torque of drilling in all of the steels employed in the test, but the amount of the reduction is influenced by the factor of machineability.* Thus the medium carbon steel with which the minimum reduction in torque (8.3 per cent) from an increase in helix angle from 26 to 45 degrees occurs, has a machineability corresponding to a drill torque of 103.0 ft. lb., while the low-carbon nickel steel with which the maximum reduction in torque (31.6 per cent) occurs has a machineability corresponding to a torque of 139.8 ft. lb. At a corresponding drilling rate the reduction in torque from a change in helix angle from 26 to 45 degrees is 15.3 per cent in drilling gray cast iron, the machineability of which corresponds to a torque of 49.0 ft. lb. As lip angles invariably are less in tools for cutting steel than in those for cutting gray cast iron it is interesting to observe that increasing the helix angle produces a smaller reduction in the torque required for drilling steels of low machineability than in that required for drilling medium gray cast iron. In steels

*See definition of machineability in Section 16, p. 50.

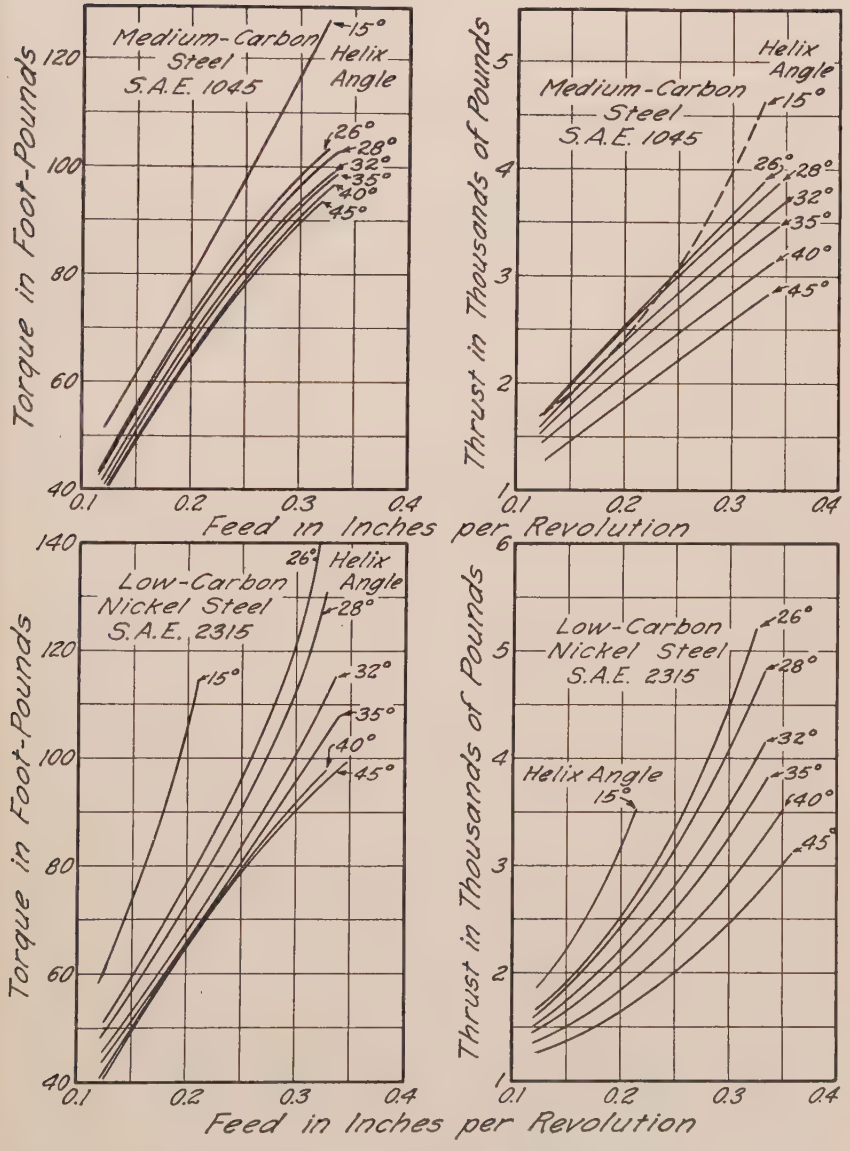


FIG. 22. VARIATION OF TORQUE AND THRUST WITH FEED, FOR DRILLS WITH VARIOUS HELIX ANGLES, IN TWO GRADES OF STEEL

of high machineability the effect on torque of increasing the helix angle is shown by the tabulation above. While these results are definitely established by the tests, no explanation of them can be advanced in the absence of exact information relating to the action of cutting tools on the structure of metals.

Considering the universal practice of making certain cutting tools with lesser lip angles for steels than for gray cast iron it may be logical to assume that the twist drill should be so constructed. The tests do not support this assumption; instead, they go to prove that twist drills with helix angles of 32 degrees or more are equally effective in both types of metal. Smaller helix angles than this produce unnecessarily large torque in drilling. A comparison of the torque of the test drills at various feeds in medium-carbon steel and in low-carbon nickel steel is presented in Fig. 22.

Thrust on the end of the drill is a factor which has little effect on power consumption, and apparently, from the data available, it exercises small influence on drill endurance. It can not be stated, however, that thrust is not responsible, under some conditions, for break down of the cutting edge and also for unnecessary drill breakage. At heavy feeds the total thrust carried by the drilling machine may result in misalignment of shafts, overheating of bearings, and breakage of parts. It is only within recent years that the drilling machine has been made stiff enough to resist thrust without distortion of the column and sufficiently powerful to drive high speed drills to capacity. With large drills and heavy feeds the thrust developed by the drill may be over 10 000 lb.; in the tests herein reported the largest thrust recorded was 8750 lb. for the 26-degree helix angle drill at a feed of 0.0320 in. per rev., and a speed of 480 r.p.m., in medium-carbon steel.

Helix angle also exercises a pronounced effect on thrust in drilling steel as indicated by the values given in Table 11, and shown graphically in Fig. 21. Referring to the latter it is observed that the thrust decreases progressively as the helix angle is increased, neglecting a number of unexplained values obtained from the 15-degree helix angle drill at lower feeds. At the highest feed (0.0320 in. per rev.) the effect on thrust of increasing the helix angle is greatest, but it varies considerably in the steels tested as is shown by the thrust curves in Fig. 22. The comparative effect of helix angle on thrust in drilling various steels is revealed by the following tabulation of the per cent reduction in thrust resulting from an increase in the helix angle from 26 to 45 degrees (feed 0.0320 in. per rev., speed 300 r.p.m.):

Steel, grade			Per Cent Reduction
Low-carbon	S.A.E.	1025	39.5
Medium-carbon	S.A.E.	1045	28.1
Low-carbon Nickel	S.A.E.	2315	46.8
Medium-carbon Nickel	S.A.E.	2345	41.3
Chromium Nickel	S.A.E.	3130	21.1
Chromium Vanadium	S.A.E.	6145	23.4
Chromium	U.M.A.	5	36.2

It will be observed that increasing the helix angle from 26 to 45 degrees reduces thrust in drilling for all of the test steels by large but varying amounts. For the low-carbon nickel steel (Brinell hardness 134) the reduction is from 5080 lb. to 2700 lb. or 46.8 per cent. The minimum reduction (21.2 per cent) occurs with the chromium nickel steel having a Brinell hardness of 163. The chromium steel (U. M. A. 5) with a Brinell hardness of 202 shows a reduction of 36.2 per cent. At a corresponding drilling rate the reduction in thrust in medium gray cast iron (Brinell hardness 146) is 30.3 per cent. There is no apparent relation between the total thrust load induced by the drill and the hardness of the metal (Brinell number), and no recorded data to indicate that the factor of hardness affects the amount of reduction in thrust accomplished by increasing the helix angle of the drill. A comparison of the thrust at various feeds on the end of the test drills in two commonly used steels is shown in Fig. 22.

Power consumption at the drill point in drilling steel, as in drilling gray cast iron, is influenced more by helix angle than by any other factor. As explained in Section 11, torque is an approximate measure of the power consumed by the drill, hence the torque values for drills of different helix angles indicate the relative power required to drive them. The actual power consumed at the drill point of the test drills at various feeds, in medium-carbon steel and in low-carbon nickel steel is shown in Table 12 and graphically in Fig. 23. These steels represent the extremes in machineability (of those tested) and the power values given may be considered as typical for driving a 1-in. drill into steel at various drilling rates. At the three feeds employed in the test, power consumption at the drill point decreased as the helix angle was increased from 26 to 45 degrees in proportion to the amount of power required to drive the drill. Thus in the low-carbon nickel steel, which has a high machineability factor,* the saving in power consumption by increasing the helix angle from 26 to 45 degrees was 31.8 per cent, while in the medium-carbon steel it was but 8.5 per cent. The latter steel has a low

*See Section 16, p. 50.

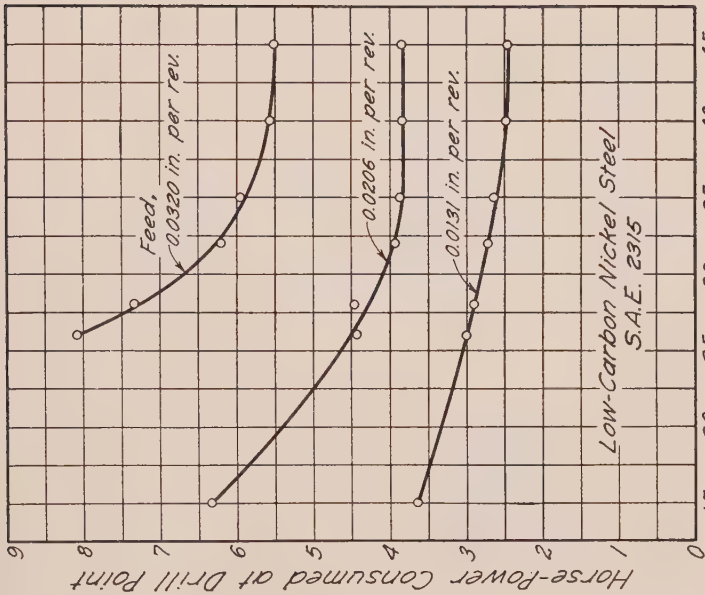
TABLE 12

POWER CONSUMPTION OF DRILLS WITH VARIOUS HELIX ANGLES
Drilling Two Different Steels

Helix Angle, deg.	Total H.P. at Drill Point					
	Medium-carbon Steel S.A.E. No. 1045			Low-carbon Nickel Steel S.A.E. No. 2315		
	Feed, in. per rev.			Feed, in. per rev.		
	0.0131	0.0206	0.0320	0.0131	0.0206	0.0320
15	3.16	4.67	7.25	3.65	6.34	....
26	2.90	4.21	5.97	3.01	4.44	8.10
28	2.91	4.32	5.78	2.93	4.47	7.34
32	2.62	3.97	5.63	2.73	3.96	6.23
35	2.51	4.00	5.62	2.65	3.88	5.99
40	2.44	3.88	5.46	2.49	3.85	5.58
45	2.63	3.79	5.46	2.47	3.85	5.52

machineability factor and requires 35.7 per cent less power (using the 26-degree angle drill) to drill at a feed of 0.0320 in. per rev. than the low-carbon nickel steel. It is obvious that increasing the helix angle from 26 to 45 degrees materially reduces the power consumption of the drill, but that the amount of the reduction varies with the machineability factor of the metal drilled.

15. *Endurance Test in Steel.*—This test was conducted in medium-carbon steel, S.A.E. 1045, to determine the relative endurance of drills with helix angles of 15, 26, 28, 32, 35, 40, and 45 degrees respectively. The test procedure was similar to that employed in the corresponding test with gray cast iron. All drills were ground alike by machine to the specifications in Table 3. The outside corners of drills were not rounded. The drilling rate was: speed 480 r.p.m., feed 0.0320 in. per rev. A heavy stream of water was directed into the drill hole from above. Drills were run to absolute destruction of the cutting edge under identical operating conditions. The total depth drilled and the values of torque and thrust at the beginning and end of the test are shown in Table 13. These results are presented graphically in Figs. 24 and 25. From a study of the graph it is apparent that in drilling medium-carbon steel at a cutting speed of 124 ft. per min. helix angle is not the deciding factor in drill endurance. It appears from the results of this particular drilling experiment that drills with helix angles above 35 degrees and below 28 degrees possess less endurance than those with helix angles between these limits. The conventional drill with a helix angle of 26 degrees and a correspondingly



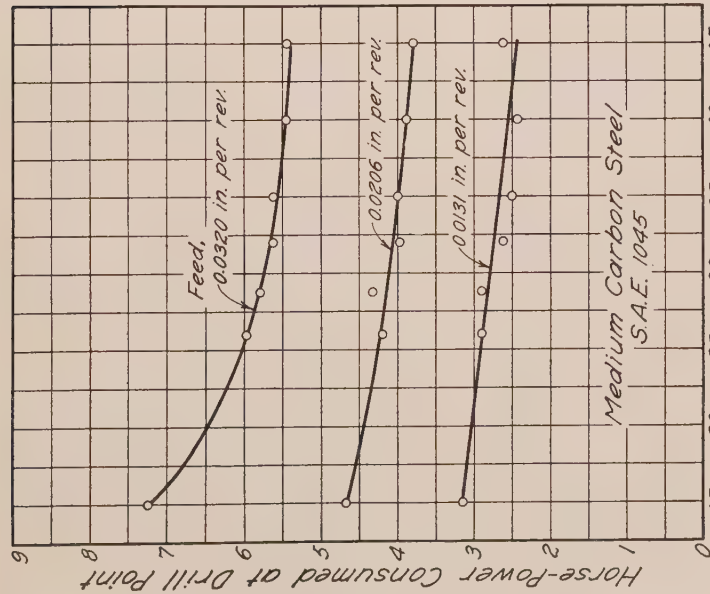


FIG. 23. POWER CONSUMPTION AT THE DRILL POINT OF DRILLS WITH VARIOUS HELIX ANGLES, IN TWO GRADES OF STEEL

TABLE 13

RELATIVE ENDURANCE OF DRILLS WITH VARIOUS HELIX ANGLES

Drilling S.A.E. 1045 Steel
Speed 480 r.p.m. Feed 0.0320 in. per rev.

Helix Angle, deg.	Total Depth Drilled, in.	Torque, ft-lb.		Thrust, lb.	
		Start	Finish	Start	Finish
15	1.00	150	Broke	5100	Broke
26	8.35	105	200	4750	8750
28	33.40	103	235	4150	8700
32	18.90	92	270	3750	6400
35	21.05	100	235	3800	8600
40	7.55	100	180	3600	5200
45	5.60	102	160	3100	3900

large lip angle shows only slightly better endurance than the 40-degree helix angle drill having a lip angle of 14 degrees less. It would seem that, at this drilling rate and in this grade of steel, there is no direct relation between size of lip angle and drill endurance. As the drilling rate used in this test is above that corresponding to ordinary shop practice these endurance results should be compared with those obtained in the helix angle test, in which the drills were operated at a normal shop rate of 300 r.p.m.

The relative permanence of the cutting edge and the torsional strength of the drills was demonstrated by the helix angle test in steel. At the close of the test the experimental drills (except the 28-degree drill which was broken accidentally) appeared as shown in Fig. 26. Except for the helix angle all drills were made to the same specifications (see Table 3). The amount of metal in each drill is approximately the same but the distribution of the metal for resistance to torsion is apparently proportional to the degree of helix angle. While the 15- and 26-degree drills eventually broke down completely, the 45-degree drill lost only $\frac{1}{8}$ in. of its length from grinding. Damage to the cutting edge of the latter was so slight that but little grinding was necessary to bring it back to standard condition. Proportionately more grinding was required to renew each of the drills of 40-, 35-, and 32-degree helix angles, indicating that at ordinary drilling rates the stability of the cutting edge is improved by increasing the helix angle of the drill above 26 degrees.

16. *Machineability of Metals.*—Machineability is a term used to designate the resistance of the structure of metals to the action of cutting

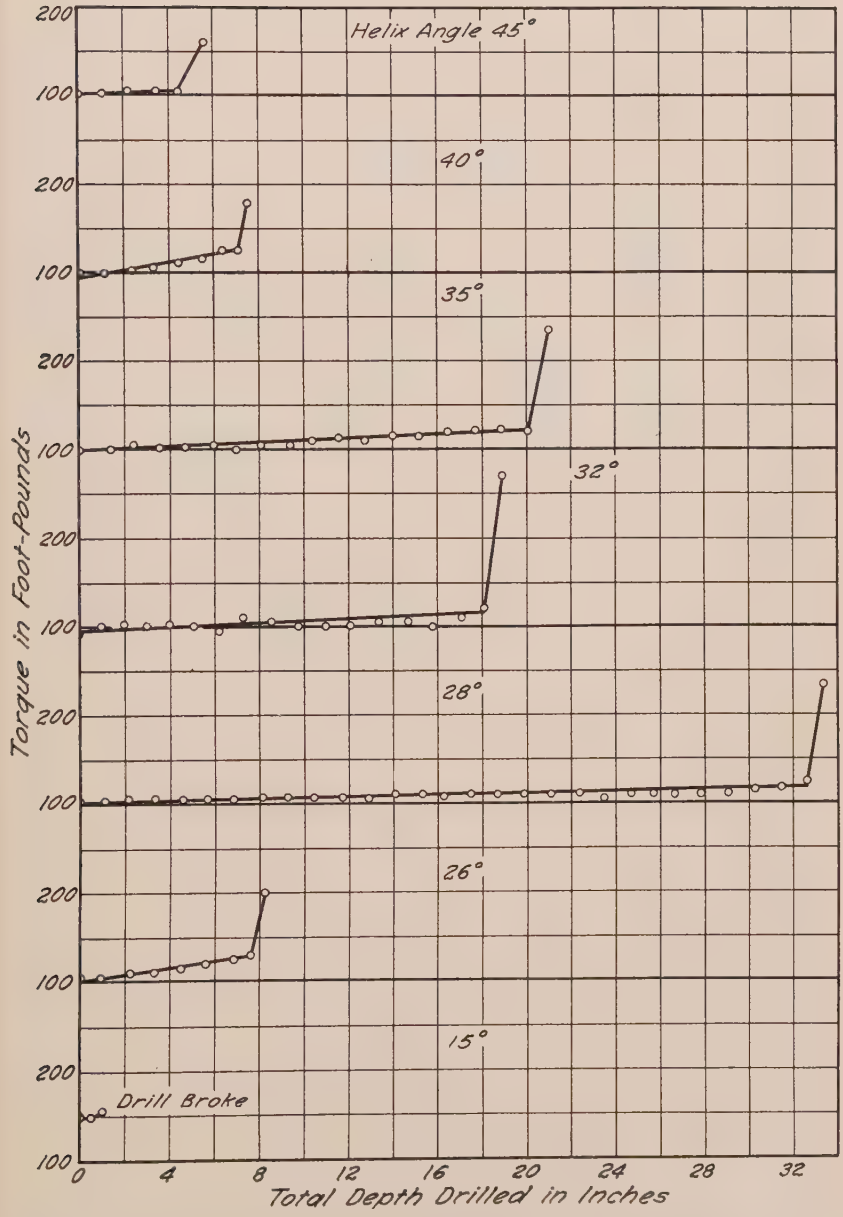


FIG. 24. TORQUE OF DRILLS WITH VARIOUS HELIX ANGLES IN ENDURANCE TEST, IN MEDIUM-CARBON STEEL

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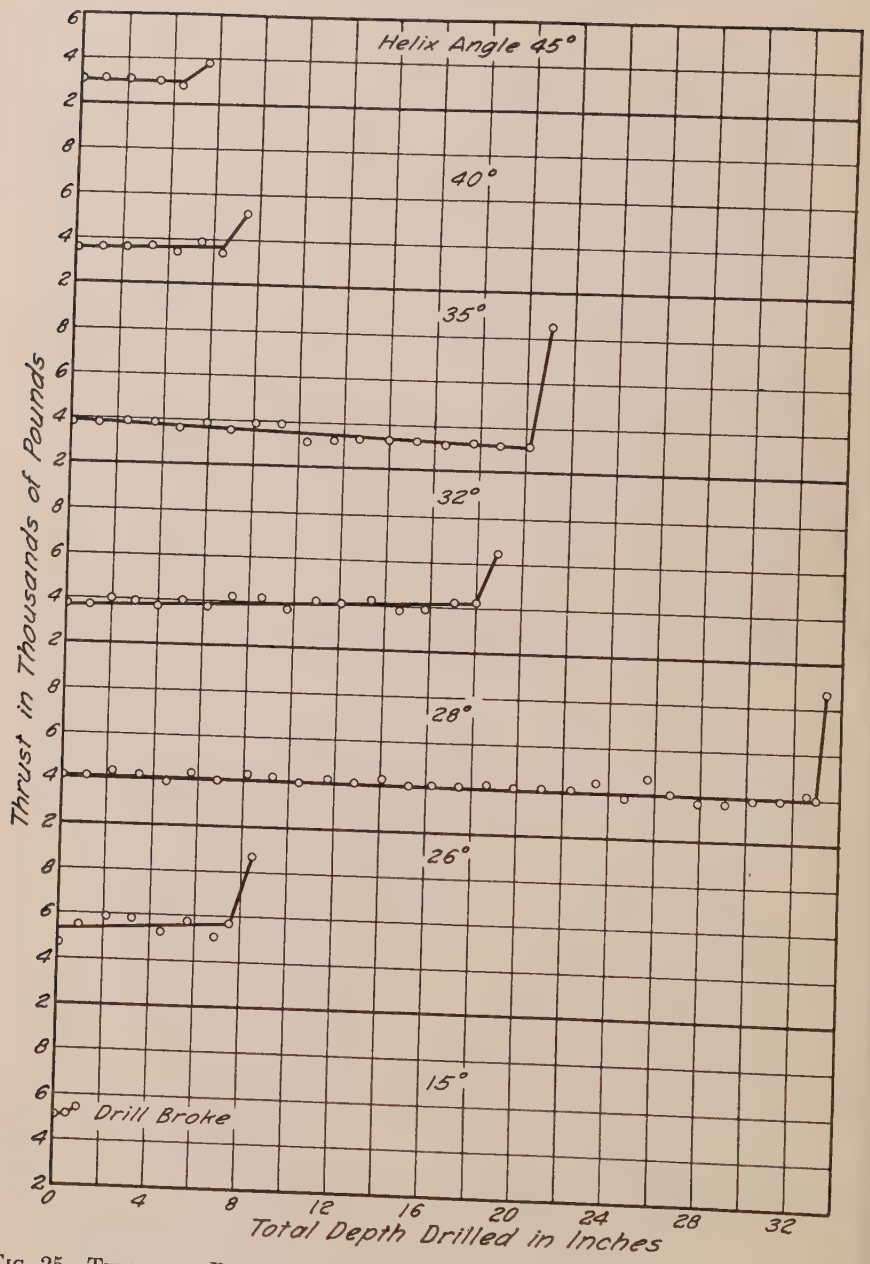


FIG. 25. THRUST OF DRILLS WITH VARIOUS HELIX ANGLES IN ENDURANCE TEST, IN MEDIUM-CARBON STEEL

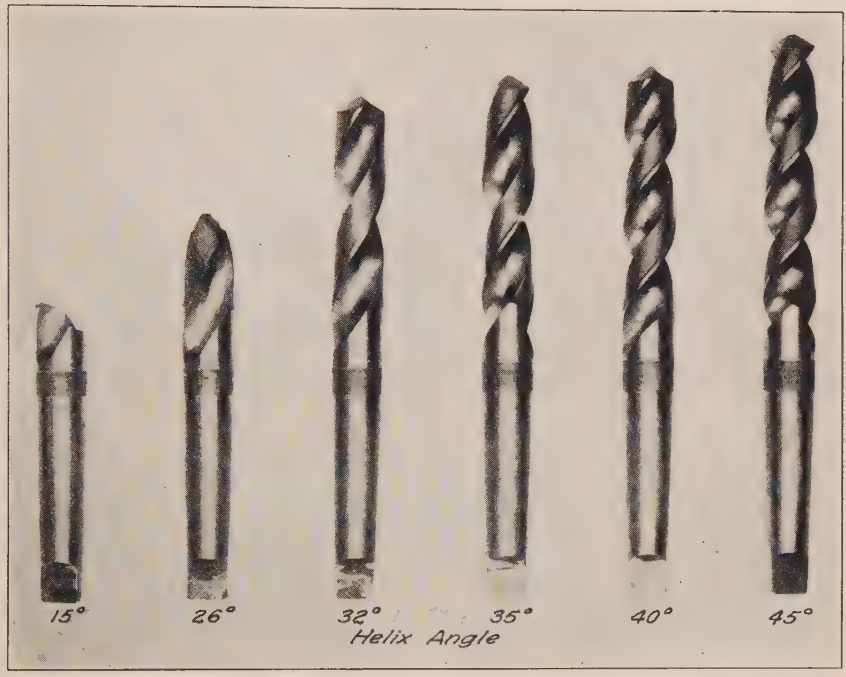


FIG. 26. CONDITIONS OF TEST DRILLS AT CLOSE OF ENDURANCE TEST IN MEDIUM-CARBON STEEL

tools. From the shop standpoint, machineability and hardness commonly are considered as synonymous terms. A "soft" metal is assumed to be "easy" to machine with a cutting tool, and vice versa. With the development of alloy steels and special foundry mixtures, however, the accepted relationship between hardness and machineability has ceased to be tenable. In fact, there is reason for believing that machineability may be dependent upon factors other than hardness as expressed by any of the conventional methods. This opinion, which has been becoming general of late, was confirmed in the case of a few steels (see Table 2) by the test primarily organized to determine the effect of helix angle on the torque and thrust of the drill. As the torque on the drill is an accurate measure of machineability, the data obtained in this test are definite though limited contributions to this subject.

The experimental data referred to are given in Table 14, and are presented graphically in Fig. 27. It is at once apparent from the graph that the machineability of the steels in question is not definitely related to their hardness (Brinell number). Why this is so cannot be explained from the present meager knowledge with reference to the machineability

TABLE 14

PHYSICAL PROPERTIES OF STEELS USED IN TEST

Torque and Thrust readings from 26-degree angle drill. Feed 0.0320 in. per rev. Speed 300 r.p.m. Steel normalized.

Test Steels	Brinell Numbers	Drill Torque ft-lb.	Drill Thrust lb.	Tensile Strength lb.
S.A.E. 1025.....	149	112.4	3620	78 000
S.A.E. 1045.....	149	103.0	3770	95 000
S.A.E. 2315.....	134	139.8	5080	82 000
S.A.E. 2345.....	163	141.6	6480	132 000
S.A.E. 3130.....	163	103.6	3500	108 000
S.A.E. 6145.....	196	120.6	4320	120 000
U.M.A. 5.....	202	140.0	5500	135 000

of metals, and the scope of this investigation limits the authors to a presentation of the information obtained with but brief comment. With the exception of the chromium steel U.M.A 5, the machineability of the steels tested, as indicated by the drill torque, appears to be unrelated to the Brinell hardness. In the case of the exception mentioned, chromium steel U.M.A. 5., both torque and hardness readings are high,

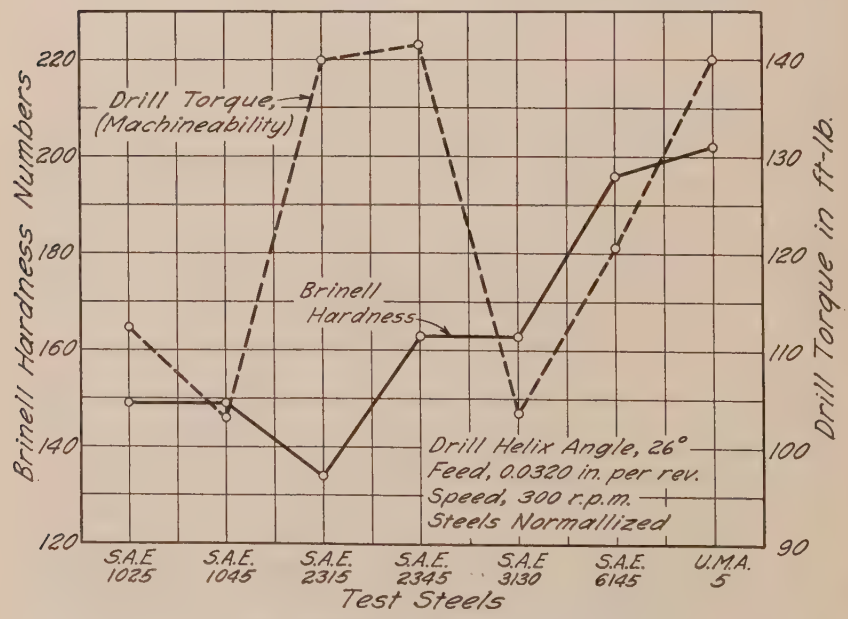


FIG. 27. COMPARISON OF MACHINEABILITY AND HARDNESS OF SEVEN GRADES OF STEEL

and although this steel is difficult to drill at a feed of 0.0320 in. per rev. (speed, 300 r.p.m.) it is more readily machineable than medium-carbon nickel steel, S.A.E. 2345, which has a Brinell hardness 19.3 per cent lower. The torque of the drill measures the force required to separate the chip from the mass and is directly proportional to the resistance offered by the structure of the metal to the mechanical action of the cutting edge of the drill. That hardness alone does not increase this resistance in certain steels is obvious, but the existing information does not warrant further deduction.

In the conduct of this test the relative machineability of the various steels was roughly indicated by the appearance of the chip. The ragged and broken chips from the steels of high machineability resembled but slightly the longer and smoother chips from the steels of low machineability. The former, as indicated by the torque readings, were removed with high lip pressures, and largely by a tearing or breaking action, which lends weight to the theory of Drs. Kessner and Heyn* that machineability depends upon the combined effect of the hardness and plasticity characteristics of the material. This latter characteristic, which tends to preserve the coherence of the crystalline structure under the application of an external force, offers an explanation for the almost complete lack of connection between machineability and hardness in the steels under observation in this test.

With the object of throwing light on the factor of machineability, the effect of the cutting action of the drill on the crystalline structure at the base of the test holes was examined microscopically. Certain test bars were sectioned through specified holes, and the area of the metal in the center which had been subjected to the crushing action of the chisel edge was photographed with a magnification of 250 diameters. The resulting micrographs are grouped in Fig. 28, and a brief description follows:

A. Gray cast iron; total carbon 3.40 per cent, combined carbon 0.52 per cent; Brinell hardness 146; unetched; typical medium soft gray iron structure; normal arrangement of crystals, only slightly distorted on the cutting plane.

B. Low-carbon steel, S.A.E.1025; carbon 0.22 per cent, manganese 0.43 per cent; Brinell hardness 149; soft annealed structure of well developed ferrite and pearlite; medium grain size; grain structure of high coherence, as shown by the elongation and distortion of crystals at the drilling edge and below it.

*Testing, v. 1, April, 1924.

C. Medium-carbon steel, S.A.E. 1045; carbon 0.37 per cent, manganese 0.66 per cent; Brinell hardness 149; large coarse pearlitic structure; crystals but slightly disturbed in a shallow plane under the drill point, indicating a low machineability factor.

D. Low-carbon nickel steel, S.A.E. 2315; carbon 0.18 per cent, nickel 3.49 per cent, manganese 0.63 per cent; Brinell hardness 134; fine annealed structure of pearlite and ferrite well distributed; grain size small; of high machineability shown by the violent distortion of crystals at the drilled edge and the dislocation of the normal structure for some distance within the body of the metal.

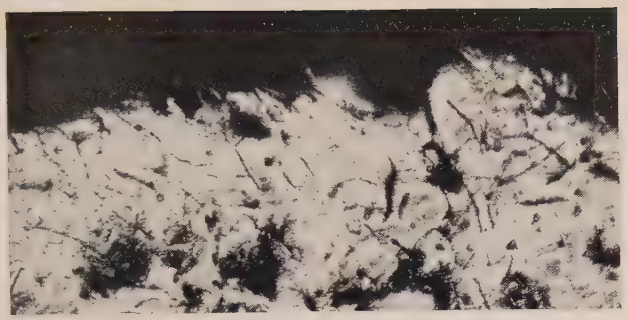
E. Medium-carbon nickel steel, S.A.E. 2345; carbon 0.48 per cent, nickel 3.45 per cent, manganese 0.61 per cent; Brinell hardness 163; very fine grain structure, pearlite predominating; distortion of crystals very marked at drill edge, but for limited depth owing to their hardness.

F. Chromium nickel steel, S.A.E. 3130; chromium 0.50 per cent, nickel 1.47 per cent, manganese 0.65 per cent; Brinell hardness 163; structure consists of an even distribution of pearlite and ferrite crystals of small and uniform size; rather extensive dislocation of crystals resulting from the drilling action. The hardness of this steel is the same as that of steel "E," but its drill torque reading is 37.4 per cent less.

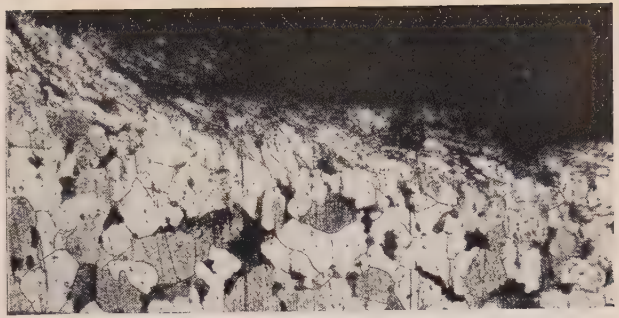
G. Chromium vanadium steel, S.A.E. 6145; chromium 1.24 per cent, vanadium 0.18 per cent, manganese 0.77 per cent; Brinell hardness 196; hard, fine grained structure, in the transition stage from sorbite to pearlite; strongly coherent, as shown by the extreme distortion of the crystals under the action of the drill. In the miniature chip the crystalline structure is completely deformed.

H. Chromium steel, U.M.A. 5; chromium 1.05 per cent, carbon 0.48 per cent, silicon 0.13 per cent, manganese 0.88 per cent; Brinell hardness 202; grain structure is small and material largely pearlite, very hard and coherent; structure breaks down in irregular forms under the influence of the drill with moderate distortion of the crystals.

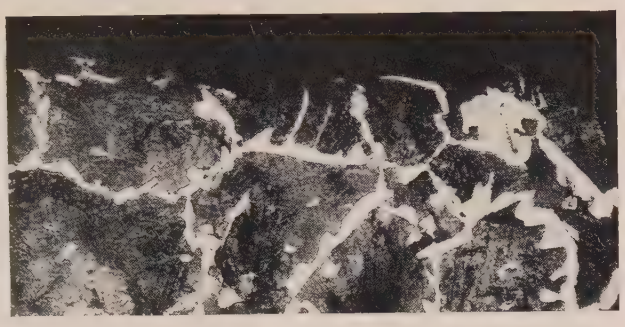
From an examination of these data it is apparent that the resistance of the crystalline structure to the deformation produced by the Brinell machine does not measure the resistance of the same structure to the action of a cutting tool.



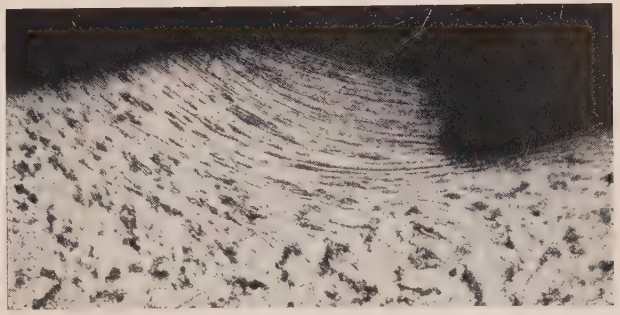
A—Gray Cast Iron, Unetched



B—Low-carbon Steel, S. A. E. 1025

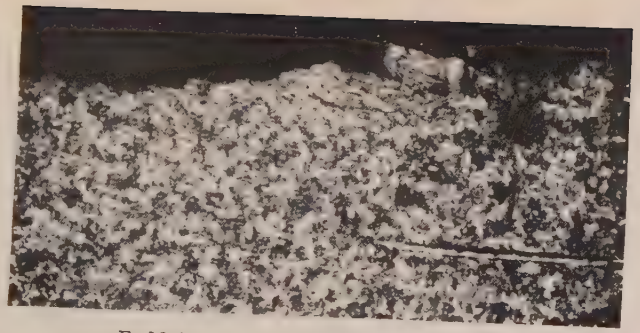


C—Medium-carbon Steel, S. A. E. 1045

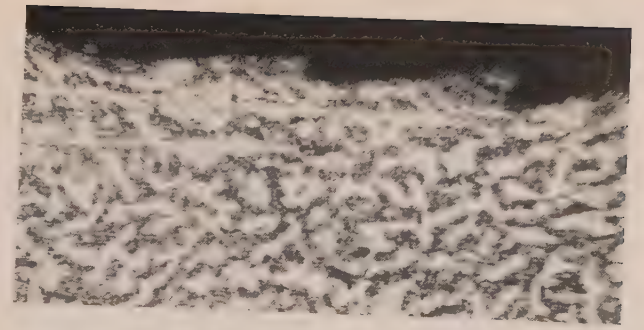


D—Low-carbon Nickel Steel, S. A. E. 2315

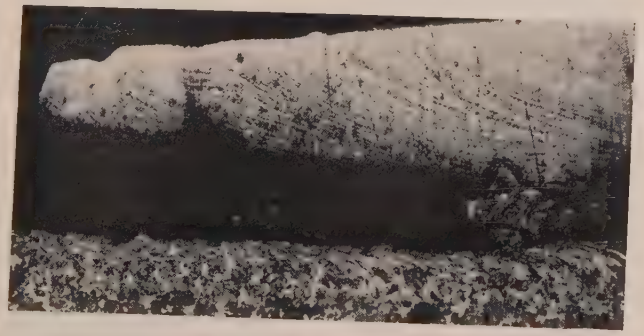
FIG. 28. MICROGRAPHS OF TEST STEELS AT BOTTOM OF HOLES UNDER DRILL POINT



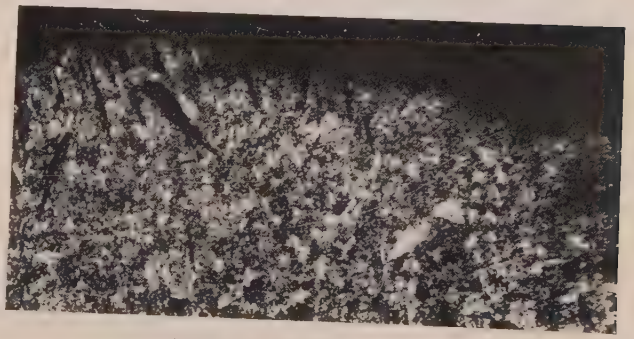
E—Medium-carbon Nickel Steel, S. A. E. 2345



F—Chromium Nickel Steel, S. A. E. 3130



G—Chromium Vanadium Steel, S. A. E. 6145



H—Chromium Steel, U. M. A. 5

FIG. 28. (Concluded). MICROGRAPHS OF TEST STEELS AT BOTTOM OF HOLES UNDER DRILL POINT

17. *Summary of Results of Tests in Steel.*—The following observations were made during these tests:

(1) Torque and thrust decreased progressively as the helix angle was increased for all the steels drilled in the test; both were lowest when the helix angle was 45 degrees.

(2) At the highest rate of feed used, 0.0320 in. per rev., increasing the helix angle from 15 to 45 degrees resulted in reducing the drill torque by 8.3 per cent in steel having a low machineability factor* (medium-carbon steel), and by 31.6 per cent in steel having a high machineability factor (low-carbon nickel steel).

(3) For the same drilling rate, increasing the helix angle from 15 to 45 degrees resulted in reducing thrust on the end of the drill by 21.1 per cent in chromium nickel steel of low machineability, and by 46.8 per cent in low-carbon nickel steel of high machineability.

(4) Savings in power consumption at the drill point due to increasing the helix angle from 26 to 45 degrees ranged from 8.5 per cent in steel of low machineability to 31.8 per cent in steel of high machineability at a drilling rate of 0.0320 in. per rev.

(5) Drill endurance was not affected by changes in helix angle from 26 to 45 degrees, inclusive, at normal drilling rates, and in steels of low machineability. At the higher drilling rates, in certain carbon and alloy steels, drills with helix angles above 35 degrees or below 28 degrees showed reduced endurance.

IV. Conclusions

18. *Summary of Conclusions.*—As a result of this investigation the following general conclusions may be drawn:

(1) Power consumption at the drill point in drilling gray cast iron or steel decreases as the helix angle is increased from 15 to 45 degrees, the amount of power consumed being lowest in drills with helix angles of 45 degrees.

(2) Saving in power consumption at the drill point resulting from the use of the larger helix angles varies with the machineability* of the metal and with the drilling rate. This saving at large feeds in steels of high machineability will exceed 30.0 per cent, in steels of low machineability, 8.0 per cent, and in gray cast iron, 25.0 per cent. At lower drilling rates the saving is approximately proportional to the rate of feed.

*See Section 16, p. 50.

(3) The torque on the drill and the thrust on the end of the drill decrease progressively as the helix angle is increased from 15 to 45 degrees, and both are at a minimum in drills with helix angles of 45 degrees.

(4) Possible reductions in the torque on the drill by increasing the helix angle from 26 to 45 degrees, at large but practicable drilling rates, will exceed 20.0 per cent in gray cast iron, 8.0 per cent in steel of low machineability, and 30.0 per cent in steel of high machineability.

(5) Possible reductions in the thrust on the end of the drill by increasing the helix angle from 26 to 45 degrees, at large but practicable drilling rates, will exceed 21.0 per cent in gray cast iron, 28.0 per cent in steel of low machineability, and 41.0 per cent in steel of high machineability.

(6) Drill endurance in drilling gray cast iron or steel is not materially affected by changes in helix angle from 26 to 45 degrees inclusive, when drilling at normal rates in metals of uniform structure. In certain carbon and alloy steels, at high drilling rates, the endurance of drills with helix angles above 35 degrees and below 28 degrees is less than that of drills with helix angles between these limits. The factor of endurance is governed more by the character of the materials drilled and the conditions of drilling than by the size of the helix angle.

(7) Considering the principal factors affecting drill design, power consumption at the drill point, and endurance of the cutting edge, drills with helix angles from 32 to 35 degrees give the most satisfactory performance in gray cast iron and steel. Drills with these helix angles are equally efficient in gray cast iron and steel.

(8) There is no apparent justification for reducing the helix angle from point to shank for the purpose of increasing chip space. Chip ejection from deep holes by drills so constructed is not better than by drills with constant helix angles.

(9) A web thickness of 0.10 in., uniform from point to shank, proved adequate in this test for 1-in. high speed drills having helix angles above 32 degrees. For drills of lesser helix angles this web thickness does not give the requisite torsional strength for drilling at high rates of feed in steel.

(10) Drill torque may be taken to be an accurate measure of the machineability of metals. Apparently machineability is a factor which depends upon the combined effect of the hardness and plasticity characteristics of metals, and consequently it is not correctly measured by the Brinell number.

V. BIBLIOGRAPHY

Twist Drills and Drilling

No.	Year	Author	Title and Reference
1	1917	.....	"Results of Researches on the Design of Drills, Cutting Speeds and Steel Used." Le Genie Civil, Oct. 6.
2	1917	J. Francis	"The Care, Use and Abuse of Drills." Mechanical World, Nov. 16.
3	1919	R. Poliakoff	"Dynamometer for Testing Twist Drills." American Machinist, v. 50, p. 1132.
4	1920	.....	"The Manufacture of Twist Drills and Taps." Machinery (London), v. 15, p. 641.
5	1920	J. V. Hunter	"Making Forged High Speed Twist Drills." American Machinist, v. 52, p. 719.
6	1920	H. Willis	"The Use and Abuse of Twist Drills." Iron Age, v. 106, p. 461.
7	1920	.....	"Twist Drill Sharpening and Thinning Machine." Engineer, v. 130, p. 237.
8	1920	G. P. Blackiston	"Proper Care of Twist Drills." Boiler Maker v. 20, p. 360.
9	1921	.....	"Investigations on Drilling Machines." Werkstattechnik, v. 15, p. 241.
10	1921	.....	"The Strength of Twisted Drills." Machinery (London), v. 18, p. 244.
11	1921	.....	"Twist Drill Sharpening Machine." Engineer, v. 131, p. 674.
12	1921	B. W. Benedict	"High Angle Twist Drills." American Machinist, v. 55, p. 1775.
13	1922	H. A. Schwartz, W. W. Flagle	"Malleable Iron Drilling Data." Journal of the S.A.E., v. 11, p. 81.

TWIST DRILLS AND DRILLING (Concluded)

No.	Year	Author	Title and Reference
14	1923	.....	"Tables of Drill Cutting Speeds." Western Machinery World, v. 14, p. 160.
15	1923	G. Schlesinger	"Drilling Machines." Werkstattechnik, v. 17, p. 417, 449.
16	1924	.....	"Magnetic Analysis of Twist Drills." American Society for Testing Materials, v. 2, p 635.
17	1924	L. M. Francis	"Speeds and Feeds for Drilling Machines." American Machinist, v. 60, p. 390.
18	1925	K. Hausler	"Twist Drills." Maschinenbau, v. 4, p. 819.
19	1925	.....	"Forging Flutes in Twist Drills." American Machinist, v. 63, p. 469.
20	1925	R. Ammon	"Determining Drilling Speeds and Feeds for Steel Castings." American Machinist, v. 63, p. 1021.
21	1925	Max Kurrien	"Drill Work and Experiments," Monatsblätter des Berliner Bezirksvereines deutscher Ingenieure. Jan. 1.

ACTION OF CUTTING TOOLS

No.	Year	Author	Title and Reference
1	1917	F. Richards	"The Cutting Tool and the Curling Chip.' Machinery, v. 23, p. 855.
2	1917	W. S. Rowell	"False Edge on Cutting Tools." Machinery v. 24, p. 47.
3	1919	C. G. Barth	"Supplement to Taylor's Art of Cutting Metals." Industrial Management, v. 58, pp. 169, 282, 369, 483. v. 59, pp. 49, 153, 222, 395, 483. v. 60, pp. 49, 218, 365.
4	1920	R. E. Crompton	"Cutting Edges of Tools." Engineering, v. 110, p. 292.
5	....	A. L. DeLeeuw	"Metal Cutting Tools." American Machinist, v. 54, pp. 1, 87, 166, 276, 316, 360, 418, 452, 508, 541, 610, 732, 807, 897, 985. v. 55, pp. 4, 134, 222, 267, 461, 517, 551, 600, 640, 682.
6	1921	.....	"The Diamond as a Cutting Tool." Engineering Production, v. 2, p. 521.
7	1921	E. J. Wild	"Origin and Calculation of Working Pressure with Single Cutter Tools." Based on Recent Experiments. Betrieb, v. 3, p. 467.
8	1921	.....	"Selection and Proper Use of Cutting Tools." Canadian Machinery, v. 26, p. 36.
9	1922	E. G. Coker, K. C. Chakko	"An Account of Some Experiments on the Action of Cutting Tools." Proceedings of the Institute of Mechanical Engineers, v. 1, p. 567.
10	1922	E. G. Coker K. C. Chakko	"Action of Cutting Tools." Engineering, v. 113, p. 564.
11	1923	.....	"Power Required for Cutting Metals." Mechanical Engineer, v. 45, p. 35.
12	1923	J. F. Kayser	"Wear and Failure of Cutting Edges." Birmingham Metallurgical Society, v. 8, p. 257.

Action of Cutting Tools (Continued)

No.	Year	Author	Title and Reference
13	1923	.....	"Research on Cutting Tools." Engineer, v. 135, pp. 95, 154.
14	1923	W. E. Splain	"Metal Cutting Tools." American Machinist, v. 58, p. 663.
15	1923	J. H. Rodgers	"Grinding and Setting Metal Cutting Tools." Canadian Machinery, v. 29, pp. 14, 28.
16	1923	M. E. Erskin	"Requirements in Cutting off Metal." Machinery, v. 29, p. 863.
17	1923	H. A. Schwartz, W. W. Slagie	"Tool Temperature and Cutting Resistance of Metals." American Machinist, v. 59, 319.
18	1923	A. A. Dowd, F. W. Curtis	"Tool Engineering." American Machinist, v. 59, p. 613. v. 60, pp. 59, 135, 259.
19	1923	C. A. Beckett	"Research in the Art of Cutting Metals." American Society of Mechanical Engineers Advance Paper for Meeting, Dec. 3.
20	1924	J. Airey	"Present Status and Future Problems of the Art of Cutting Metals." Mechanical Engineer, v. 46, p. 160.
21	1924	H. J. Stoewer	"Cutting Edge Formation." Werkstattechnik, v. 18, pp. 484, 522.
22	1924	J. A. Hall	"Research in Cutting Metals." Mechanical Engineer, v. 46, p. 640.
23	1925	T. E. Stanton, J. H. Hyde	"Cutting Tool Research." Engineering, v. 119, p. 148.
24	1925	A. C. Sturney, W. Rosenhain	"Flow and Rupture During Cutting." Engineering, v. 119, pp. 151, 178.
25	1925	.....	"Philosophy of Cutting." Engineer, v. 139, p. 163.
26	1925	W. Hippler	"Scientific Design of Tools." Zeitschrift des Vereines deutscher Ingenieure, v. 69, p. 227.

ACTION OF CUTTING TOOLS (Concluded)

No.	YEAR	AUTHOR	TITLE AND REFERENCE
27	1925	W. Hippler	"Present State of the Science of Cutting Metals." Maschinenbau, v. 4, p. 156.
28	1925	H. Shore	"Thermoelectric Measurement of Cutting Tool Temperatures." Washington Academy of Science, v. 15, p. 85.
29	1925	E. G. Coker	"Cutting Tool Research." Engineering, v. 119, pp. 363, 403.
30	1925	O. W. Boston	"Research in Metal Cutting." American Machinist, v. 63, p. 805.
31	1925	Gottwein	"Measuring the Cutting Temperature in Cutting Low Carbon Steel." Maschinenbau, v. 4, p. 1129.
32	1926	.....	"Effect of Wear on Small Tools." Industrial Management, (London), v. 13, p. 29.
33	1926	E. G. Herbert	"The Measurement of Cutting Temperatures." American Machinist, v. 64, pp. 281, 307, 363.
34	1926	W. R. Ward	"Cutting Action and Tools." American Society for Steel Treating, v. 9, p. 482.

LATHE TOOLS

No.	Year	Author	Title and Reference
1	1917	L. E. Gilmore	"Testing Tools for Lathes." American Machinist, v. 46, p. 779.
2	1917	R. Poliakoff	"Lathe Tool Problems." Iron Trade Review, v. 61, p. 709.
3	1918	A. L. Jenkins	"Alignment Chart for Lathe Tools." American Machinist, v. 48, p. 456.
4	1920	G. W. Burleg	"Cutting Power of Lathe Tools." Journal of the Institute of Mechanical Engineers, v. 10, p. 755.
5	1921	.....	"Boring Tools: General Considerations." American Machinist, v. 54, p. 276.
6	1921	.....	"Grinding Lathe and Planer Tools." Machinery, (London), v. 17, p. 418.
7	1921	H. Sack	"Study of Lathe Tool Cutting Pressures." Betrieb, v. 3, p. 800.
8	1922	J. B. Conway	"Chart for Determining Pressure Exerted by Boring Tools." American Machinist, v. 56, p. 476.
9	1923	D. Smith	"Lathe Tool Research." Engineering, v. 115, p. 137.
10	1923	.....	"Lathe Tool Design." Engineering, v. 115, p. 146.
11	1923	H. Klopstock	"Investigation of Turning." Werkstattechnik, v. 17, pp. 645, 666.
12	1923	H. J. French, J. Strauss	"Lathe Breakdown Tests of High Speed Tool Steel." U. S. Bureau of Standards Technologic Paper, v. 17, p. 183.
13	1925	J. Fitzen	"Investigation of Cutting Metals by Rotation." Maschinenbau, v. 4, p. 158.

LATHE TOOLS (Concluded)

No.	YEAR	AUTHOR	TITLE AND REFERENCE
14	1925	D. Smith A. Leigh	"Experiments with Lathe Tools on Fine Cuts." Engineering, v. 119, p. 364.
15	1925	D. Smith	"Lathe Tool Research." Engineer, v. 139, p. 389.
16	1925	H. Klopstock	"Investigation in Turning and Planing." Mechanical Engineer, v. 47, p. 474.

LUBRICATION AND COOLING OF CUTTING TOOLS

No.	Year	Author	Title and Reference
1	1917	E. K. Hammond	"Lubrication of Cutting Tools." Machinery, v. 23, pp. 373, 490, 595, 701.
2	1917	.....	"Coolants for Cutting." American Machinist, v. 46, p. 280.
3	1917	C. N. Underwood	"Method of Testing Cutting Compounds." American Machinist, v. 46, p. 853.
4	1918	R. B. Hayett	"Cutting Tool Lubrication." Railway Mechanical Engineer, v. 92, p. 282.
5	1918	J. A. DeCew	"Emulsion Lubrication of Cutting Tools." American Machinist, v. 49, p. 433.
6	1918	.....	"Cutting Lubricants and Cooling Liquids." Shipbuilding and Shipping Record, v. 12, p. 445.
7	1919	R. Trautschold	"Cutting Lubricants for Machine Tools." Machinery, v. 26, p. 45.
8	1921	G. Schlesinger, E. Simon	"Investigation of Lubricants for Drilling." Werkstattechnik, v. 15, p. 140.
9	1922	E. C. Bingham	"Cutting Fluids." American Machinist, v. 56, p. 958.
10	1925	A. F. Brewer	"Lubricating and Cooling the Cutting Tool." Industrial Management, v. 69, p. 197.
11	1925	J. Jacquet	"Importance of Lubrication in Working Metals." Arts et Métiers, v. 78, p. 407.
12	1926	J. A. Maguire	"Compounds for Cutting, Grinding and Rust Prevention." Machinery, v. 32, p. 478.

MACHINEABILITY OF METALS

No.	YEAR	AUTHOR	TITLE AND REFERENCE
1	1916	L. E. Stanton, R. G. Batson	"Hardness Tests Research." Engineering, v. 102, p. 556.
2	1917	F. Robin	"Research on Method of Determining Hardness by Penetration of a Circular Cutter." Société d'Encouragement pour l'Industrie Nationale, March and April.
3	1917	C. H. Bierbaum	"How Drill Tools Displace the Grain of Bearing Metals." American Machinist, v. 47, p. 665.
4	1917	F. Jeffries	"The Effect of Great Hydrostatic Pressure on Physical Properties of Metals." Engineering, v. 104, p. 357.
5	1918	H. M. Brayton	"Tensile Strength and Hardness of Steel." Iron Age, v. 102, p. 627.
6	1920	M. Brillouin	"Theory of Plasticity and Rupture of Isotropic Solids." Annales de Physique, v. 13, p. 217.
7	1922	E. F. Lake	"Toughness in Relation to Hardness of Metals." Forging and Heat Treating, v. 8, p. 313.
8	1924	H. A. Holz	"Brinell's Researches on the Resistance of Iron and Steel to Wear." Testing, v. 1, p. 104.
9	1924	.....	"Consideration of Statistics in Testing Materials." Testing, v. 1, April.
10	1924	.....	"Resistance of Metals." Testing, v. 1, April.
11	1924	A. L. Norburg, T. Samuel	"Brinell-Tensile Relationships." Iron and Steel Institute, Advance Paper No. 12, May Meeting.

MACHINEABILITY OF METALS (Concluded)

No.	Year	Author	Title and Reference
12	1925	J. W. Bolton	"Factors Influencing the Machineability of Cast Iron." Machinery, v. 31, p. 533.
13	1925	J. Ward	"Hardness Governs Machineability." Foundry, v. 53, p. 684.
14	1925	.....	"Brinell Hardness and Tensile Strength of Cast Iron." British Cast Iron Research. Bulletin No. 10, p. 6.
15	1926	E. J. Lowry	"Machining Uninfluenced by Hardness." Iron Age, v. 117. p. 789.

MACHINING NON-FERROUS METALS

No.	YEAR	AUTHOR	TITLE AND REFERENCE
1	1925	.....	"Report on Brass Cutting Tools." Metal Industry, v. 23, p. 234.
2	1925	O. D. Burlingame	"High Speed Cutting of Brass and Soft Metals." Mechanical Engineer, v. 47, p. 705.

MILLING CUTTERS

No.	Year	Author	Title and Reference
1	1917	A. L. Jenkins	"Alignment Chart for Milling Cutters." American Machinist, v. 47, p. 94.
2	1918	G. W. Burley	"Milling Cutter Rake and Clearance." Mechanical World, March 1.
3	1918	R. Poliakoff	"Universal Milling Machine Dynamometer." Machinery, v. 24, p. 932.
4	1921	.....	"Determining Pressure Exerted by Milling Cutters." Canadian Machinery, v. 26, p. 33.
5	1921	.....	"A Milling Cutter Dynamometer." Engineer, v. 132, p. 405.
6	1921	J. Airy, C. J. Oxford	"On the Art of Milling." Mechanical Engineer, v. 43, p. 783.
7	1922	H. E. Harris	"Formed Milling Cutters with Top and Side Rake." Machinery, v. 28, p. 527.
8	1923	W. Schumann	"Milling Cutters." Praktische Maschinen Konstrukteur, v. 56, pp. 67, 99.
9	1923	B. P. Graves, J. A. Hall	"Effect of Variations in Design of Milling Cutters on Power Requirements and Capacity." Mechanical Engineer, v. 45, p. 155.
10	1923	C. F. Roby	"Chip Formation by Milling Cutters." Mechanical Engineer, v. 45, p. 586.
11	1925	G. Engel	"Cutting Speed and Pressure in Milling." Zeitschrift des Vereines deutscher Ingenieure v. 69, p. 819.

Speeds and Feeds of Cutting Tools.

No.	Year	Author	Title and Reference
1	1918	E. K. Hammond	"Feeds and Speeds for Drilling." Machinery, v. 24, p. 715.
2	1920	F. Gabriel	"Alignment Charts for Calculating Working Speeds of Machine Tools." Betrieb, v. 3, p. 155.
3	1920	.....	"Standardization of Speed Steps in Machine Tools." Praktische Maschinen Konstrukteur, v. 53, p. 155.
4	1920	A. Leistikow	"Alignment Chart for Operating Speeds." Betrieb, v. 3, p. 120.
5	1921	A. Winkel	"Standardized Calculation of Working Speeds." Werkstattechnik, v. 15, p. 5.
6	1921	.....	"Cutting Speeds for Steel and Cast Iron." Belting, v. 18, p. 72.
7	1924	.....	"Cutting Speeds." Engineering Production, v. 7, p. 26.
8	1924	H. Behr	"Alignment Chart for Speeds of Machine Tools." Werkstattechnik, v. 18, p. 294.

TESTING OF MACHINE TOOLS

No.	Year	Author	Title and Reference
1	1917	.....	"Portable Machine Tool Testing Outfit." Iron Age, v. 99, p. 121.
2	1917	C. H. Crawford	"Power Tests of Machine Tools." Railway Mechanical Engineer, v. 91, p. 294.
3	1920	C. Wasserberger	"Measurement of Power by Means of a Lathe Tool Dynamometer." Praktische Maschinen Konstrukteur, v. 53, pp. 289, 314.
4	1920	F. A. Parsons	"Power Consumed in Milling." American Machinist, v. 53, p. 315.
5	1921	W. Mitan	"A Testing Laboratory for Machine Tools." Zeitschrift des Vereines deutscher Ingenieure, v. 65, p. 268.
6	1921	A. Freund	"Efficiency Tests of Machine Tools." Betrieb, v. 3, p. 319.
7	1921	T. Damm	"Influence of Shape of Chips on the Power Consumption of Machine Tools. Werkstattechnik, v. 14, p. 507.
8	1923	F. A. Parsons	"Power Required for Cutting Metals." Mechanical Engineer, v. 45, p. 35.
9	1923	H. K. Keever	"Determining Cutting Horse Power of a Machine Tool." American Machinist, v. 59, p. 555.
10	1924	W. Mitan	"Testing Performance of Machine Tools." Maschinenbau, v. 3, p. 1115.
11	1926	J. Dalchau	"Electric Tool Testing Dynamometer." Electrotechnische Zeitschrift, v. 47, p. 36.

TOOL STEELS

No.	YEAR	AUTHOR	TITLE AND REFERENCE
1	1916	J. O. Arnold	"Efficiency of Tool Steels." Iron Age, v. 97, p. 1207.
2	1918	.....	"Tests on Tool Steel." Le Genie Civil, Jan. 5.
3	1918	P. Denis	"Research on Tool Steel Adapted to Lathe, Milling and Drilling Work." Le Genie Civil, Feb. 23.
4	1918	.....	"Stellite and High Speed Steel Compared." Iron Age, v. 102, p. 1584.
5	1919	C. P. Berg	"Relation of Heat Treatment, Design and Selection of Steels for Metal Cutting Tools." Journal of American Society for Steel Treating, v. 2, p. 7.
6	1920	G. L. Kronfield	"How to Use Stellite." American Machinist, v. 52, p. 293.
7	1920	A. J. Langhammer	"Comparative Test Upon High Speed Steels." American Machinist, v. 52, pp. 979, 1140, 1227, 1292.
8	1920	.....	"Testing High Speed Steel Stock." Machinery, v. 27, p. 228.
9	1921	T. Fish	"Testing High Speed Steel." Machinery, v. 27, p. 640.
10	1921	F. B. Foley	"Analysis of Some Drill Steel Tests." Iron and Steel of Canada, v. 4, p. 231.
11	1922	J. V. Emmons	"The Effect of Structure upon the Machining of Tool Steel." Journal of American Society for Steel Treating, v. 2, p. 1100.
12	1922	H. J. French, J. Strauss, T. G. Digges	"Effect of Heat Treatment on Lathe Tool Performance." Railway Mechanical Engineer, v. 96, p. 647.

TOOL STEELS (Concluded)

No.	Year	Author	Title and Reference
13	1924	J. M. Quinn	"Casting High Speed Tools." Iron Trade Review, v. 75, p. 226.
14	1924	D. Smith I. Hey	"Hardness and Cutting Trials of a Tool Steel." Engineer, v. 137, p. 366.
15	1924	H. Pommerenke, R. Dewert	"Effect of Heat Treatment on Cutting Capacity of High Speed Steels." Revue de Metallurgie, v. 21, p. 371.
16	1924	W. Oertel, F. Polzguter	"Mechanical Properties of Certain High Speed Steels in Comparison to their Cutting Efficiency." Stahl und Eisen, v. 44, p. 1708.
17	1925	R. Hohage, O. Grutzner	"Cutting Tests with High Speed Steels." Kruppsche Monatschrift, v. 6, p. 105.
18	1925	A. C. Blackall	"Research on Steels for Cutting Tools." Blast Furnace and Steel Plant, v. 13, p. 289.
19	1926	J. Strauss	"Cutting Test of Tool Steel." Journal of American Society for Steel Treating, v.9, p. 571
20	1926	.....	"Effect of High Speed Tool Steel on Machines." Iron Age, v. 117, p. 1202.

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